Optical Waveguides (OPT568)

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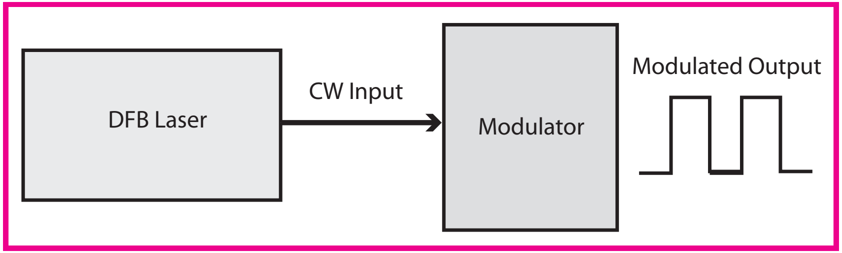
Optical Modulators

- Semiconductor waveguides useful for making amplitude and phase modulators.
- Several kinds of modulators exist:
  - ⋆ Acousto-optic modulators
  - ⋆ Electro-optic modulators
  - ⋆ Electro-absorption modulators
  - ⋆ Polymer-based modulators
- Electro-optic and electro-absorption modulators can be operated at speeds of up to 40 GHz.
- Both kinds are used routinely for fiber-optic communication systems.

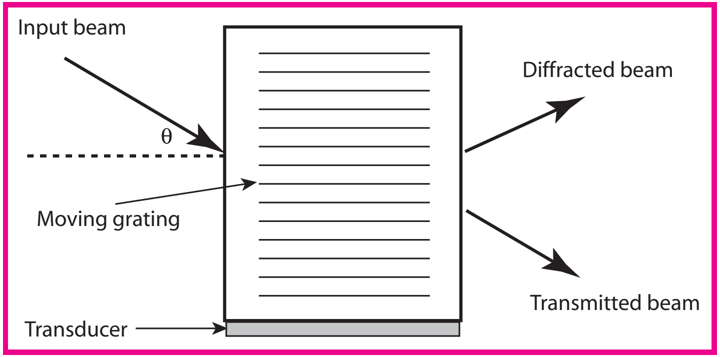
Back
Close

Modulations Schemes



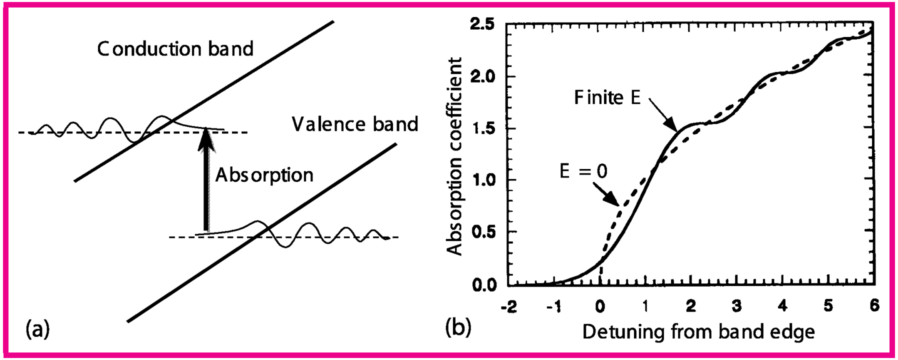
- Electromagnetic carrier: $\mathbf{E}(t) = \hat{\mathbf{e}} A \cos(\omega_0 t + \phi)$.
- Modulation of A, ω_0, or ϕ leads to AM, FM and PM, respectively.
- In the digital case, they are referred to as ASK, FSK, and PSK. ASK is also called on–off keying.
- Role of a modulator is to convert a CW input into an optical signal that mimics applied electrical signal.
- A good modulator must exhibit high extinction ratio, large bandwidth, low chirp, and a low bias voltage.

Photo-Elastic Effect



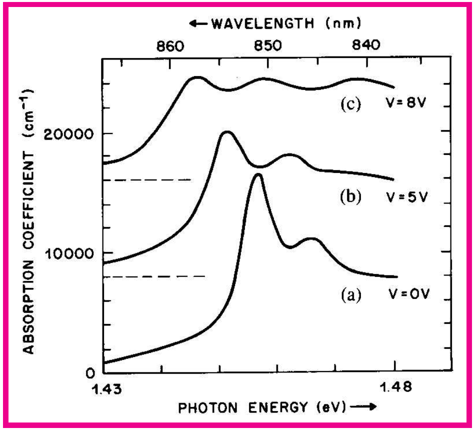
- Refractive index changes because of elastic strain induced by an acoustic wave.
- Index changes $\sim 10^{-4}$ feasible for $LiNbO_3$.
- Moving index grating creates a frequency shift ∼100 MHz for the diffracted beam.
- $LiNbO_3$ waveguides can be used for making acousto-optic modulators but bandwidth is limited to below 0.5 GHz.

Electro-Absorption Effect



- Absorption coefficient changes with applied voltage.
- Franz–Keldysh effect: Bandgap of a semiconductor decreases when a dc electric field is applied across it.
- Mathematically, wavefunction takes the form of an Airy function.
- Exponentially decaying tails, in effect, reduce the bandgap.
- Sharp absorption edge becomes more gradual.

Electro-Absorption in Waveguides



- For thin waveguides, quantum-well effects become important.
- Excitonic effects dominate in the spectral region below the bandgap.
- Quantum-confined Stark effect: Change in the absorption spectrum with applied field.
- Modulator uses a semiconductor whose bandgap is slightly larger than photon energy.

Electro-Refraction Effect

- Refractive index changes with applied voltage.
- Physical phenomenon: Pockels effect (electro-optic effect).
- Described in terms of impermeability tensor $\eta_{ij} = 1/\varepsilon_{ij}$.
- Impermeability tensor changes with dc electric field as

$$\eta_{ij}(\mathbf{E}) = \eta_{ij}^{(0)} + \sum_k r_{ijk} E_k + \sum_{kl} s_{ijkl} E_k E_l,$$

- Pockels effect is governed by the tensor r_{ijk}.
- As r_{ijk} is symmetric in i and j, a 6×3 matrix r_{hk} is used.
- $h = 1,2,3$ for $i = j$ (diagonal elements) and $h = 4,5,6$ for off-diagonal elements η_{23} η_{31}, and η_{12}.

Electro-optic Coefficients

- Changes in refractive index n with applied dc field governed by

$$\Delta\left(\frac{1}{\varepsilon_h}\right) \equiv \Delta\left(\frac{1}{n_h^2}\right) = \sum_{k=1}^{3} r_{hk} E_k.$$

- 18 elements of the matrix r_{hk} describe electro-optic properties of a crystal.
- Only a few of them are nonzero depending on symmetry group.
- For crystals with $\bar{4}3m$ symmetry (GaAs and InP), a single parameter r_{41} describes all electro-optic properties.
- For crystals with $3m$ symmetry ($LiNbO_3$), three parameters are needed.

Electro-Optic Coefficients

- Full form of matrix r_{hk} for $LiNbO_3$ and GaAs:

$$r_{hk}(3m) = \begin{pmatrix} 0 & -r_{22} & r_{13} \\ 0 & r_{22} & r_{13} \\ 0 & 0 & r_{33} \\ 0 & r_{42} & 0 \\ r_{42} & 0 & 0 \\ r_{22} & 0 & 0 \end{pmatrix}; \qquad r_{hk}(\bar{4}3m) = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ r_{41} & 0 & 0 \\ 0 & r_{41} & 0 \\ 0 & 0 & r_{41} \end{pmatrix}.$$

- Numerical values of nonzero elements depend on wavelength.
- $r_{41} = 1.1$ pm/V for GaAs at 0.9 μm, but this value increases to 1.43 pm/V near 1.3 μm.
- For InP, $r_{41} = 1.45$ pm/V at 1.06 μm, but this value decreases to 1.3 pm/V near 1.3 μm.

Induced Birefringence

- Consider a GaAs waveguide with light propagation along the crystallographic axis [001].
- Index ellipsoid takes the form:

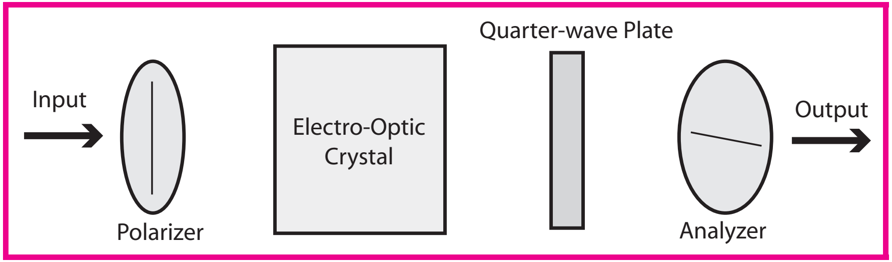
$$\frac{x^2}{n^2}+\frac{y^2}{n^2}+\frac{z^2}{n^2}+2r_{41}Exy=0.$$

- After rotation by 45°, we obtain $\frac{x'^2}{n_x^2}+\frac{y'^2}{n_y^2}+\frac{z^2}{n^2}=0.$
- Modified refractive indices n_x and n_y are given by

$$n_x \approx n+\tfrac{1}{2}n^3 r_{41}E, \qquad n_y \approx n-\tfrac{1}{2}n^3 r_{41}E.$$

- GaAs becomes birefringent with applied dc field.

Electro-Optic Modulator

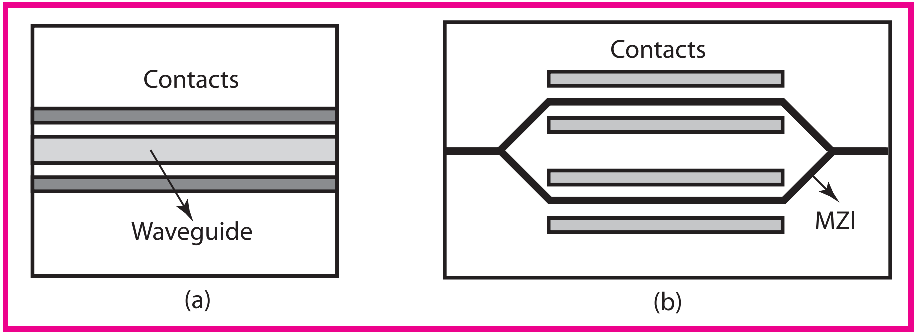


- Index changes induced by dc electric field produce phase shifts that are different for TE and TM modes.
- State of polarization at the output changes, and the change can be controlled by the applied field.
- Polarization changes can be translated into amplitude modulation by placing waveguide between two polarizers.
- Bulk electro-optic modulators use this technique with a KDP crystal.

Electro-Optic Waveguide Modulators

- $LiNbO_3$ waveguides are commonly used for making modulators.
- Electro-optic response of $LiNbO_3$ is governed by four parameters.
- Near 1.5 μm $r_{13} = 8.6,\ r_{22} = 3.4,\ r_{33} = 30.9,\ r_{42} = 28$ pm/V.
- Electric field applied along the crystallographic z axis to select r_{33}.
- Refractive index along this axis is modified by $\Delta n = -\frac{1}{2}n^3 r_{33} E$.
- Using $n \approx 2.2$ and $r_{33} = 30.9$ pm/V, $\Delta n/E \sim 10^{-4}$ μm/V.
- Optical phase of changes by $\Delta\phi = (2\pi/\lambda)\Delta n L$ for a modulator of length L.
- PM can be converted into AM using a Mach–Zehnder configuration.

Lithium Niobate Modulators



- Phase modulator: A single waveguide of suitable length.
- Amplitude modulator: two waveguides in MZ configuration.
- Important design parameter V_π: Voltage applied across electrodes to produce a π phase shift.
- Index change $\Delta n = -\frac{1}{2}\Gamma n^3 r_{33}(V/d_e)$ for electrodes separated by d_e.
- Γ accounts for partial overlap between the optical and electric fields (typically $\Gamma = 0.5$).

Temporal Response of Amplitude Modulators

- For 3-dB couplers with $\rho_1 = \rho_2 = \frac{1}{2}$, transmitted power $P(t) = P_{\max} \sin^2 \frac{1}{2}[\phi_b + \kappa V(t)]$.
- Bias phase shift ϕ_b introduced by applying a constant dc voltage.
- Constant κ governs modulation efficiency.
- If $\phi_b = \pi/2$, a nearly linear response is possible:

$$P(t) = \tfrac{1}{2} P_{\max}\{1 - \sin[\kappa V(t)]\} \approx \tfrac{1}{2} P_{\max}[1 - \kappa V(t)].$$

- Insertion loss and extinction ratio are defined as

$$\alpha_{\text{ins}} = -10 \log_{10}(P_{\max}/P_{\text{in}}), \quad r_{\text{ex}} = -10 \log_{10}(P_{\min}/P_{\max}).$$

- Modern $LiNbO_3$ modulators can provide 20 dB extinction ratio with insertion loss $<$5 dB.

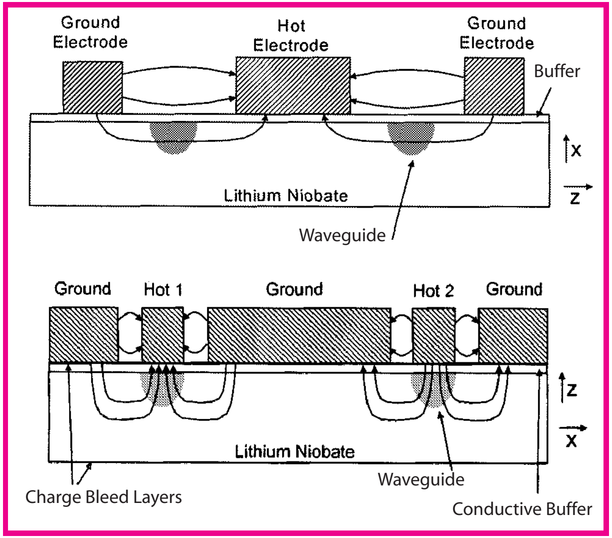
Modulator-Induced Chirp

- AM Modulators can also impose frequency chirp (PM).
- For a balanced MZ interferometer field transmitted is given by

$$A_3(t) = A_0\{\sqrt{\rho_1\rho_2}\exp[i\phi_1(t)] - \sqrt{(1-\rho_1)(1-\rho_2)}\exp[i\phi_2(t)]\},$$

- $\phi_1(t)$ and $\phi_2(t)$ are voltage-induced phase shifts in two arms.
- $A_3(t) = iA_0\exp[\frac{1}{2}i(\phi_1+\phi_2)]\sin[\frac{1}{2}(\phi_1-\phi_2)]$ when $\rho_1 = \rho_2 = \frac{1}{2}$.
- If $\phi_1 = 0$ or $\phi_2 = 0$, modulator output is chirped.
- When $\phi_2 = -\phi_1$, chirp-free modulation occurs.
- At the same time, a π phase shift occurs at half the voltage.
- Such modulators are referred to as push–pull modulators.

Modulator Design

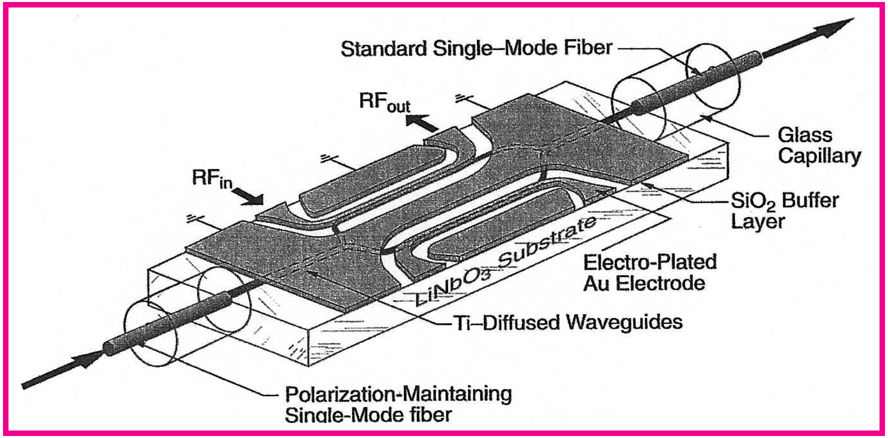


- Configurations for x-cut and z-cut $LiNbO_3$ modulators.
- In x-cut design, side electrodes are grounded.
- If index increases in one arm, it decreases in the other.

Modulator Design

- In the case of z-cut $LiNbO_3$, electric field is oriented along z axis by placing hot electrodes directly over two waveguides.
- With this configuration, electric field points perpendicular to the substrate surface.
- Overlap between optical and electric fields enhanced, resulting in reduced V_π voltage.
- Buffer layer between electrodes and waveguides is essential to ensure that mode does not penetrate into metallic layer.
- Piezoelectric and pyroelectric effects lead to accumulation of electric charges at the substrate surfaces.
- A charge-bleed layer is used at the bottom of the substrate to solve this problem.

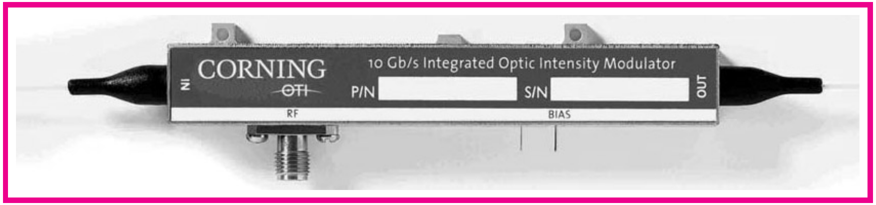
Modulator Design



- $LiNbO_3$ modulators operating at 10 Gb/s or more employ a RF transmission line in the form of a coplanar waveguide.
- Such modulators are referred to as traveling-wave modulators.
- Input and output ends MZ interferometer are connected to two fiber pigtails to form an all-fiber device.

Modulator Design

- Design of modulators requires optimization of several parameters.
- Refractive index of $LiNbO_3$ is 2.2 at optical frequencies but increases to 6 at microwave frequencies.
- A silica buffer layer is used to reduce velocity mismatch ($n = 1.9$ at microwave frequencies).
- Commercial modulators are compact (width 1.5 cm, length 12 cm) and require $<$5 V at 10 Gb/s.
- Modulators operating at bit rates of 40 Gb/s available since 2000 but require $>$10 V.

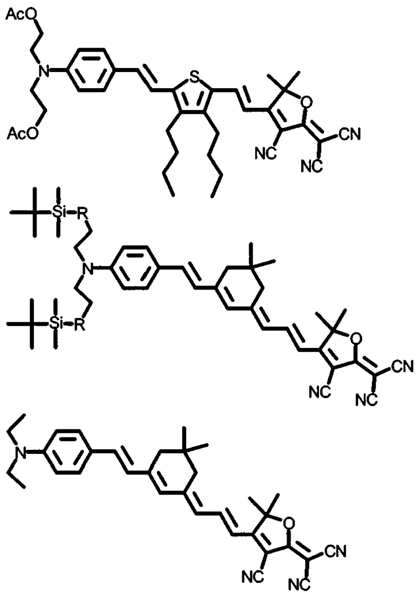


Back
Close

Polymer-Based Modulators

- Modulators making use of polymer waveguides offer a number of advantages over $LiNbO_3$.
- These include low dielectric constant at microwave frequencies, high electro-optic coefficient, low operating voltage, and low cost.
- Unfortunately, polymers do not exhibit Pockels effect.
- A nonlinear chromophore is incorporated into polymer matrix.
- Situation similar to erbium-doped fibers as chromophore molecules are not attached to the polymer backbone.
- Three most commonly used chromophores are known as FTC, CLD-1, and CLD-72.

Structure of Chromophores



FTC

CLD-1

CLD-72

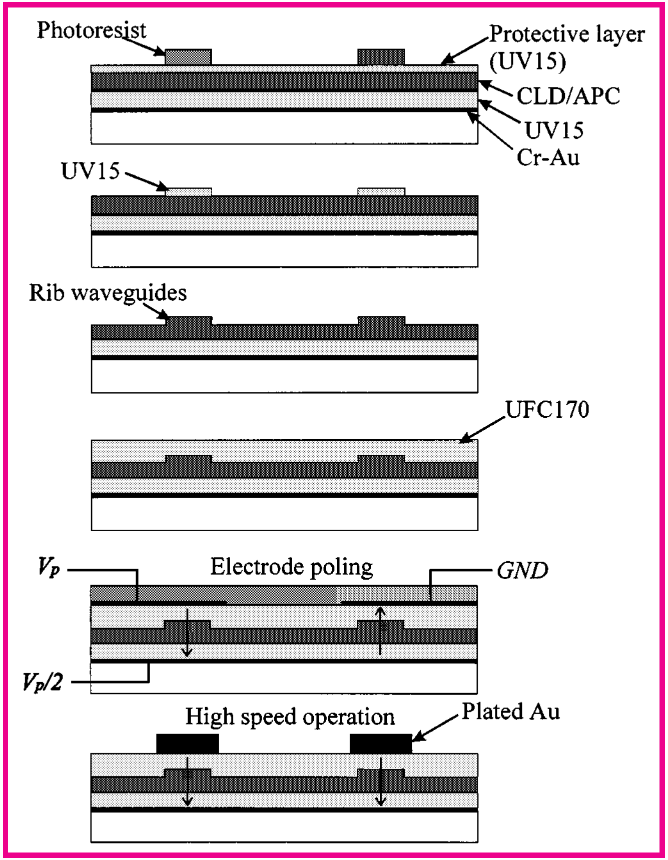
- A poling field used to aligns chromophore molecules and to produce a permanent dipole moment.
- r_{33} larger compared with $LiNbO_3$.

Back
Close

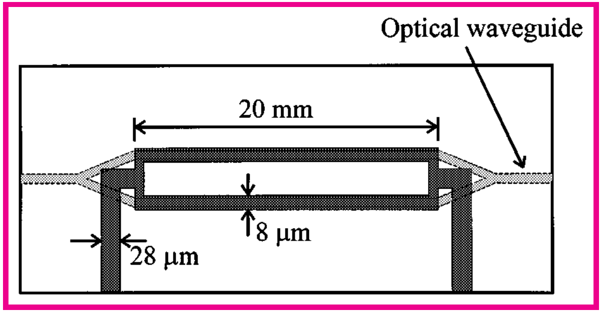
Device Fabrication

- Core layer is sandwiched between two cladding layers made using another polymer with a lower refractive index.
- Chromophores doped into the core polymer host (PMMA).
- Bottom cladding layer is made with a UV-curable epoxy (UV15).
- Upper cladding layer requires a different polymer because it should not contain small molecules that affect core layer.
- A polymer known as UFC170 has been found suitable for this purpose. It can be cured with a small dosage of UV light.
- Refractive indices are 1.504, 1.612, and 1.488 starting from bottom cladding layer.

Fabrication Steps

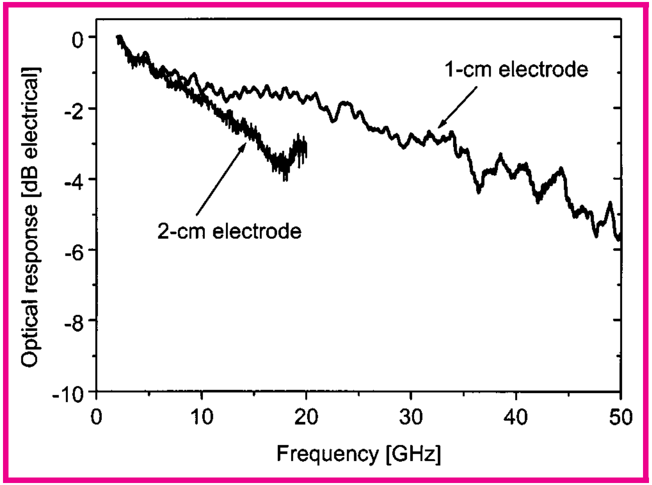


Fabrication Steps



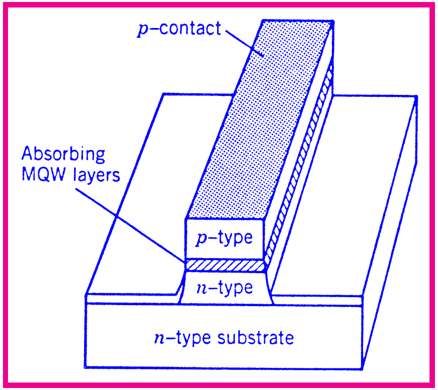
- Final step requires construction of an RF strip line.
- Photolithography used to first etch the electrode pattern into a photoresist.
- Electrode formed using a gold layer (3–4 μm thick).
- Strip line should propagate microwaves without much loss.
- Microwave losses along the strip line set the bandwidth of polymer modulators.

Modulator Performance



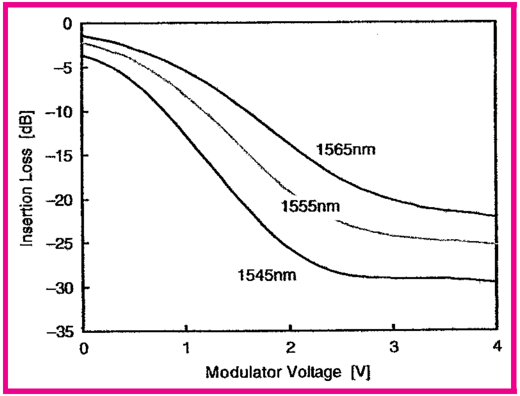
- Polymer modulators exhibit high insertion losses.
- For a 3-μm-wide and 3-cm-long core, losses exceed 9 dB.
- Can be reduced to <5 dB by optimizing waveguide dimensions.
- $V_\pi L$ below 4 V-cm; $V_\pi < 2$ V possible.
- Modulator bandwidth limited only by electronics.

Electroabsorption Modulators



- Basic design is similar to that of a semiconductor laser.
- Bandgap of quantum wells larger than photon energy.
- light completely transmitted in the absence of bias.
- Input signal is absorbed when bias is applied.
- Extinction ratio >15 dB possible with a reverse bias of 2–3 V at bit rates of up to 40 Gb/s.

Temporal Response



- Transmissivity as a function of V at three different wavelengths.
- Output power $P(V) = P_0 \exp[-\alpha(V)L_m]$.
- An EAM can respond fast if carriers generated during absorption can be removed from the active region quickly.
- EAMs can be operated at bit rates of 40 Gb/s.
- α limits the operating wavelength range to 20 nm or so.

Digital Modulation

- $V(t)$ changed between two values to produce 0 and 1 bit.
- On-state power $P_1 < P_{in}$ because of insertion losses.
- Insertion loss is defined as

$$\alpha_{ins} = -10\log_{10}(P_1/P_{in}).$$

- Minimum power P_0 may not be zero for a digital modulator.
- Extinction ratio or on–off ratio is defined as

$$r_{ex} = -10\log_{10}(P_0/P_1) \approx 4.343 L_m[\alpha(V_0) - \alpha(V_1)].$$

- Modern EAM can provide on–off ratio >20 dB with insertion losses below 5 dB.

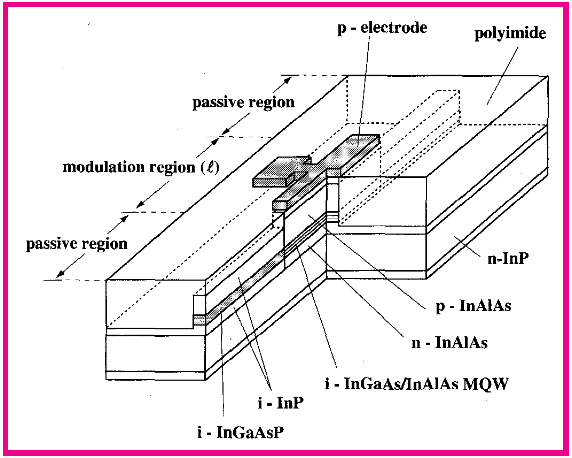
Modulation-Induced Chirp

- In practice, AM is accompanied with PM.
- Changes in absorption produce changes in refractive index through the Kramers–Kronig relation

$$\Delta n(\omega) = \frac{c}{\pi} \int_0^\infty \frac{\Delta\alpha(\omega')}{\omega'^2 - \omega^2} d\omega'.$$

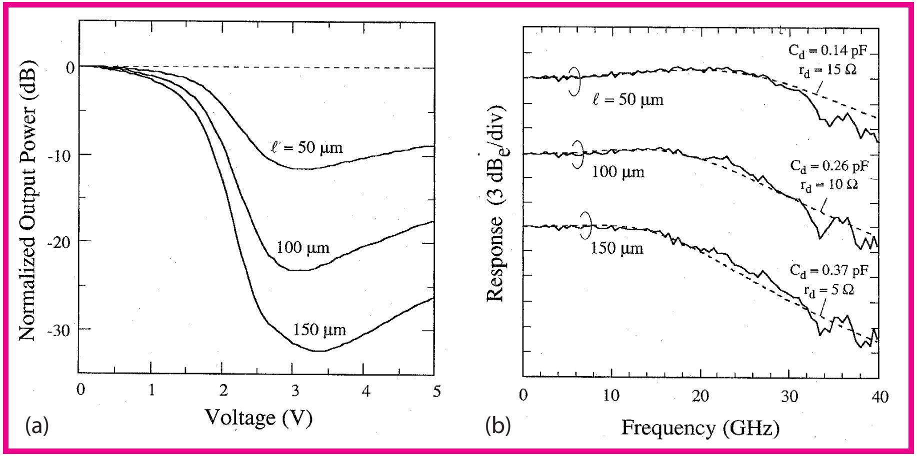
- Since Δn changes with time, optical phase ϕ also changes across the pulse.
- Fortunately, chirp is not very large for EAMs.
- It can be controlled by using strained quantum wells.

Modulator Design



- A MQW EAM integrated with passive waveguides at the input and output ends.
- MQW region consists of ten 8-nm-thick $In_{0.48}Ga_{0.52}As$ quantum-well layers separated by 5-nm barrier layers.
- Quantum wells under tensile strain because of 0.35% lattice mismatch; it helps to reduce applied voltage.

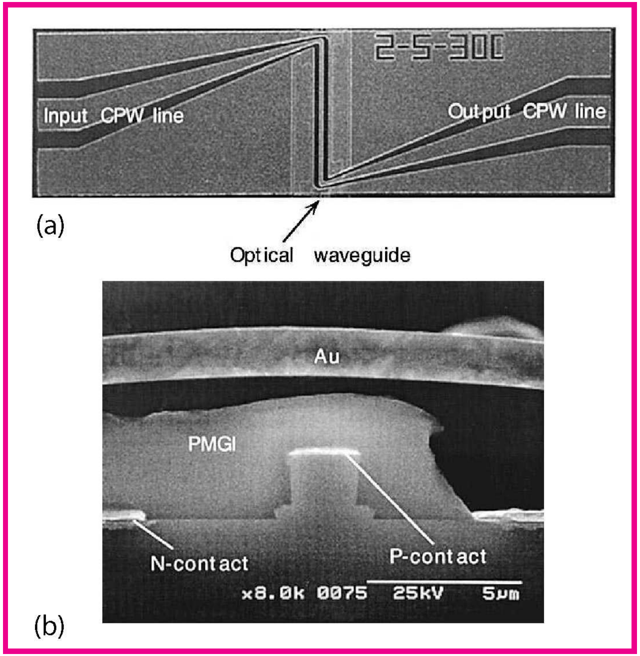
Modulator Performance



- Both the extinction ratio and bandwidth depend on length of modulation section.
- Extinction ratio is reduced for shorter lengths.
- However, modulation bandwidth increases from 20 GHz to 33 GHz.
- Such modulators can operate at 40 Gb/s but with a reduced extinction ratio.

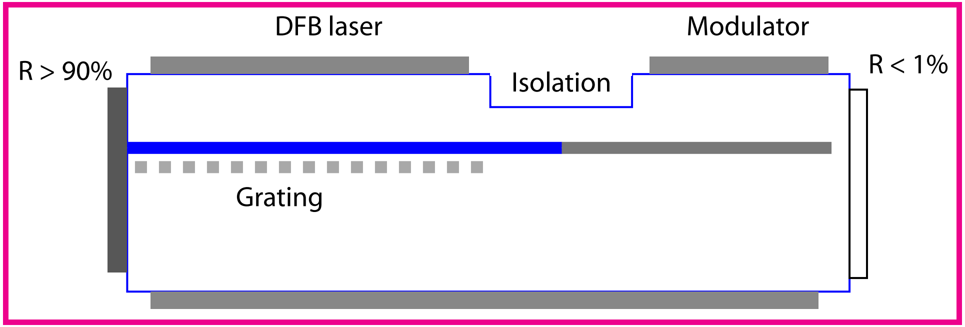
Back
Close

Traveling-Wave EAMs



- Microwaves propagated using a coplanar-waveguide (CPW) line.
- Bandwidths larger than 50 GHz have been realized while keeping driving voltage below 2 V.

Integration of EAM with Laser



- EAM and laser can easily be integrated on the same chip to reduce insertion losses.
- An SOA can be integrated on the same chip to compensate for residual losses.
- By 1999, 10-Gb/s transmitters with integrated EAM became available commercially.
- By 2001, such integrated modulators exhibited a bandwidth of more than 50 GHz.

Electrical Crosstalk

- Performance of modulator-integrated DFB lasers limited by optical and electrical crosstalk.
- Typically, separation between electrical contacts is $<$0.2 mm.
- Any leakage from modulator contact to laser contact can change dc bias of the laser in a periodic manner.
- Such unwanted changes shift laser wavelength and produce chirp (laser frequency changes with time).
- Middle section should provide an isolation impedance of 800 Ω or more.
- Such values are difficult to achieve at microwave frequencies approaching 40 GHz.

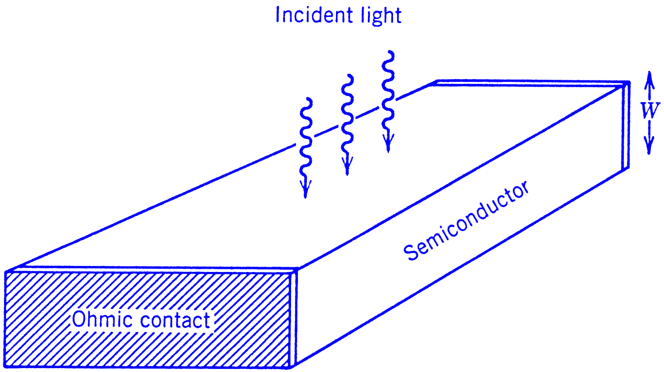
Optical Crosstalk

- Optical crosstalk results from the residual reflectivity of output facet (AR-coated in practice).
- This residual reflectivity is seen by the laser only when modulator lets light pass through it.
- As a result, laser gain and wavelength are slightly different during each on–off cycle.
- This creates an additional source of frequency chirping.
- It can be eliminated if the front facet has a residual reflectivity of less than 0.01%.
- Difficult to realize in practice.

Photodetectors

- A photodetector converts optical signal into electrical domain.
- Physical mechanism: photoelectric effect.
- A photodetector should have high sensitivity, fast response, low noise, low cost, and high reliability.
- These requirements are best met by photodetectors made using semiconductor waveguides.
- In contrast with lasers, indirect-bandgap semiconductors can be used to make photodetectors.
- Commonly used materials: Si, Ge, GaAs, InP.

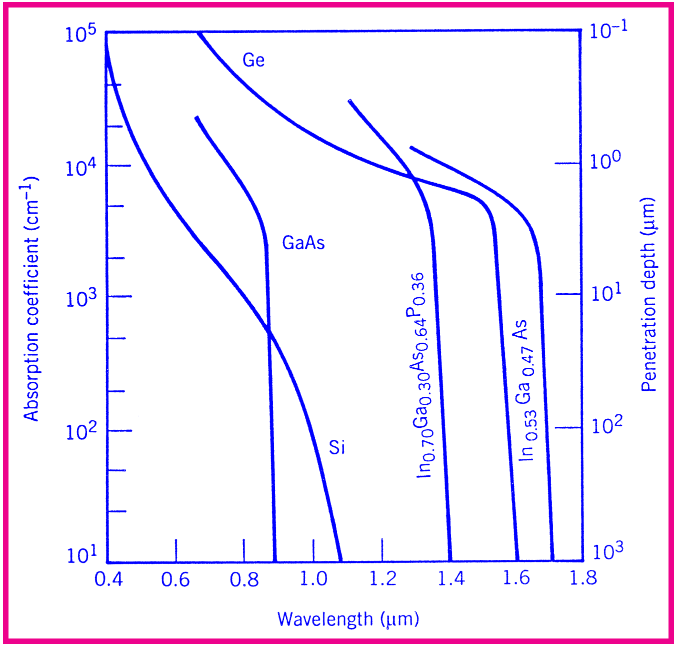
Photoelectric effect



- A semiconductor layer absorbs incident light if $h\nu > E_g$.
- Electron–hole pairs collected by applying voltage.
- Photocurrent $I = R_d P_{in}$ (R_d measures responsivity).
- Quantum Efficiency: $\eta = \frac{I/q}{P_{in}/h\nu} = \frac{h\nu}{q} R$.

$$\eta = \frac{P_{abs}}{P_{in}} = \frac{P_{in} - P_{tr}}{P_{in}} = 1 - \exp(-\alpha W).$$

Absorption in Semiconductors



- Absorption occurs for $\lambda < hc/E_g$.
- Large absorption coefficient for most semiconductors.
- Layer thickness $< 5\ \mu$m sufficient in practice.

Rise Time and Bandwidth

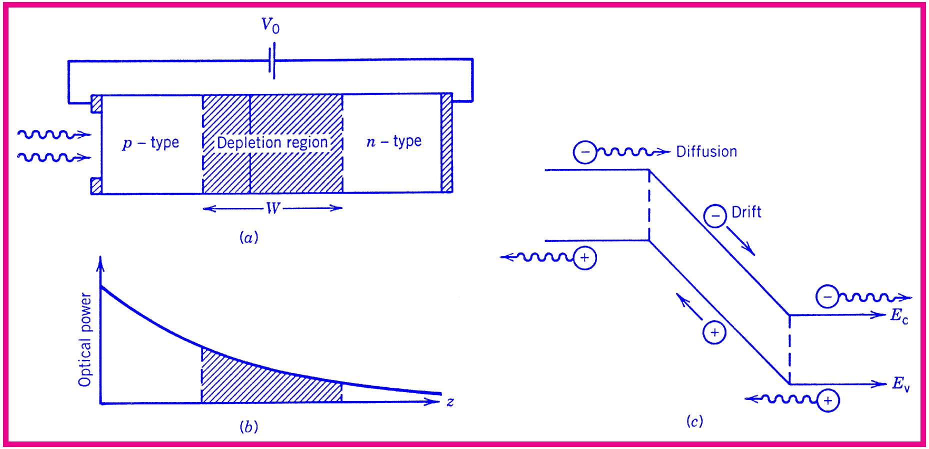
- All detectors have a finite bandwidth.
- Rise Time: Time over which the current builds up from 10 to 90% of its final value when optical power is changed abruptly.
- Limited by the transit time and RC time constant:

$$V_{\text{out}}(t) = V_0[1 - \exp(-t/RC)].$$

- RC circuit rise time: $T_r = (\ln 9)RC \approx 2.2\tau_{RC}$.
- Photodetector rise time: $T_r = (\ln 9)(\tau_{\text{tr}} + \tau_{RC})$.
- Photodetector bandwidth: $\Delta f = [2\pi(\tau_{\text{tr}} + \tau_{RC})]^{-1}$.
- For $\tau_{\text{tr}} = \tau_{RC} = 100$ ps, the bandwidth is below 1 GHz.

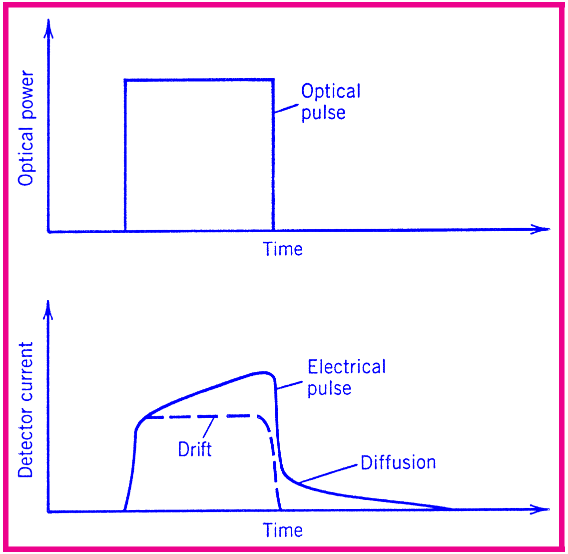
Back
Close

Photodiodes



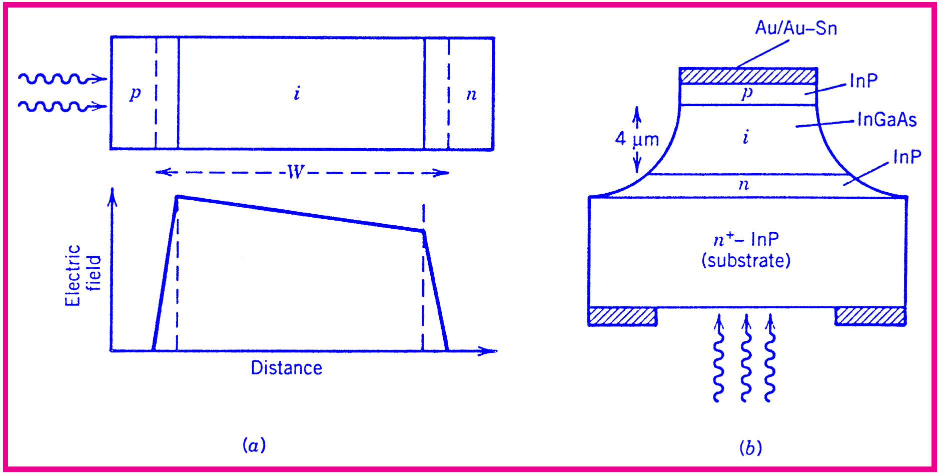
- A reverse-biased p–n junction is used.
- Electron–hole pairs in the depletion region swept by the large electric field across it (drift current).
- Electron-hole pairs outside the depletion region produce diffusion current.

Response Time of Photodiodes



- Drift current is produced quickly (transit time $<$100 ps).
- Diffusion is a relatively slow process ($\sim$1 ns).
- This mismatch leads to distortion.
- Problem can be solved using p–i–n photodiodes.

p–i–n Photodiodes



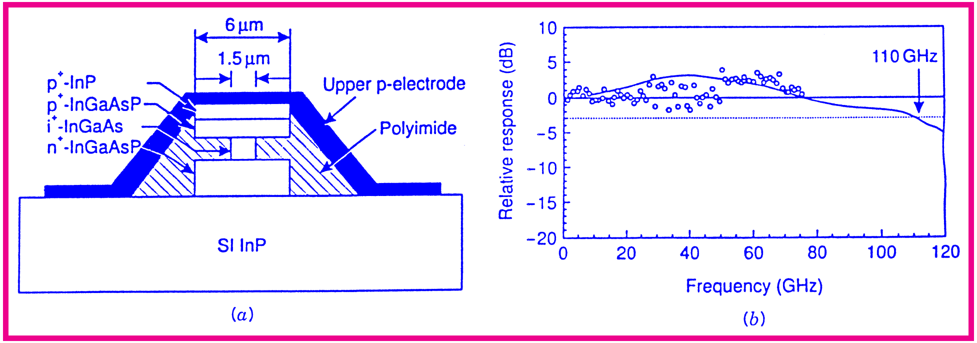
- Insert an intrinsic or i layer between the p–n junction.
- Reduce the thickness of p- and n-type layers.
- Use a higher-bandgap material for p- and n-type layers.
- No absorption in these layers if $E_g > h\nu$.

Common p–i–n Photodiodes

Parameter	Symbol	Unit	Si	Ge	InGaAs
Wavelength	λ	μm	0.4–1.1	0.8–1.8	1.0–1.7
Responsivity	R	A/W	0.4–0.6	0.5–0.7	0.6–0.9
Quantum efficiency	η	%	75–90	50–55	60–70
Dark current	I_d	nA	1–10	50–500	1–20
Rise time	T_r	ns	0.5–1	0.1–0.5	0.02–0.5
Bandwidth	Δf	GHz	0.3–0.6	0.5–3	1–10
Bias voltage	V_b	V	50–100	6–10	5–6

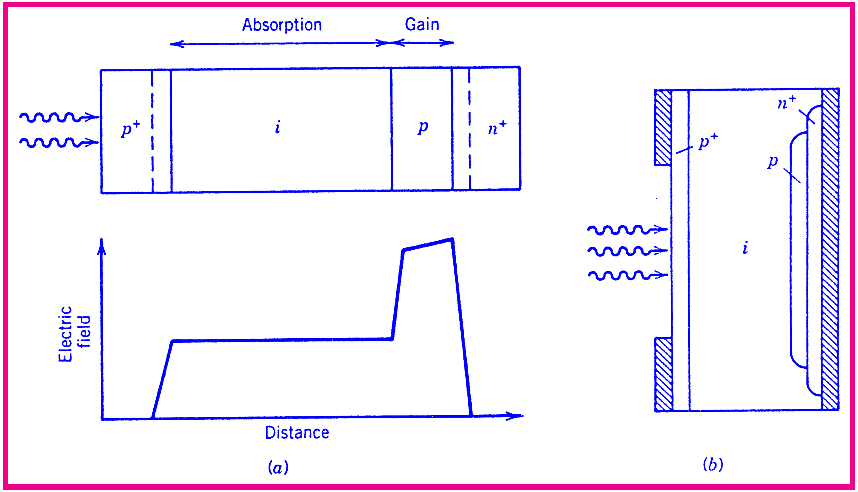
- InGaAs photodiodes used in most lightwave systems.
- Transit time < 10 ps for $W < 5$ μm.
- Bandwidth >50 GHz possible with a suitable design.

Waveguide Photodiodes



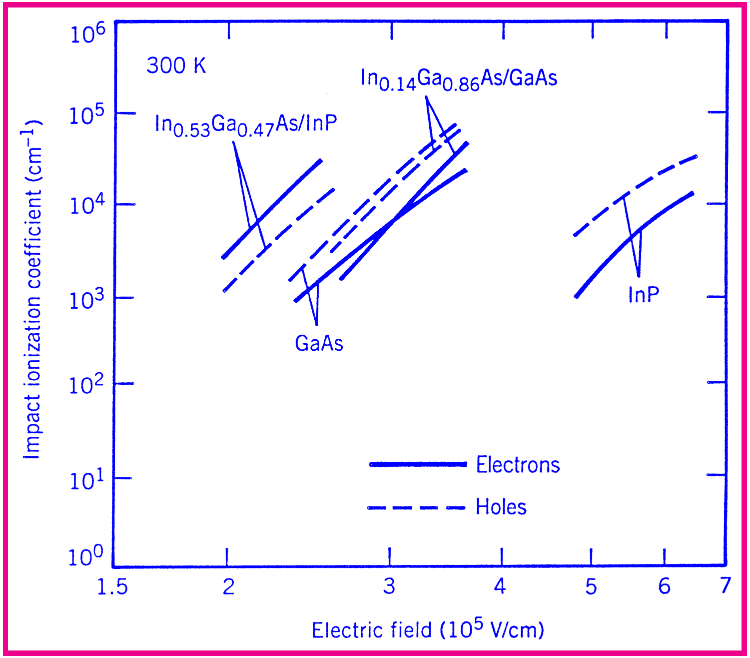
- Optical signal edge-coupled into a waveguide.
- Structure similar to that of a semiconductor laser.
- Coupling efficiency improved using a multimode waveguide.
- Bandwidth can be increased using a mushroom-mesa structure.
- $\tau_{RC} \sim 1$ ps realized by reducing parasitic capacitance and internal series resistance.

Avalanche Photodiodes



- APDs increase responsivity through internal gain.
- A single photon produces many electron-hole pairs.
- High electric field exists across the gain layer.
- Accelerating electrons and holes generate new electron–hole pairs though impact ionization.

Impact Ionization



- Kinetic energy of the electron used to create new e–h pairs.
- Impact-ionization coefficients α_e and α_h play important role.

APD Gain

- APD gain calculated using the two simple rate equations:

$$\frac{di_e}{dx} = \alpha_e i_e + \alpha_h i_h, \qquad -\frac{di_h}{dx} = \alpha_e i_e + \alpha_h i_h.$$

- Total current $I = i_e(x) + i_h(x)$ throughout the gain layer.
- Eliminating i_h: $di_e/dx = (\alpha_e - \alpha_h)i_e + \alpha_h I$.
- Solve with boundary condition $i_e(d) = I$

$$M = \frac{1-k_A}{\exp[-(1-k_A)\alpha_e d] - k_A}.$$

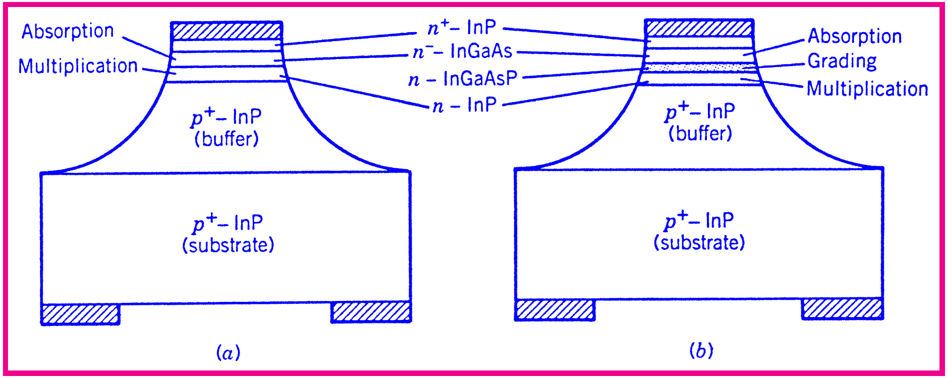
- APD gain is quite sensitive to the ratio $k_A = \alpha_h/\alpha_e$.
- $M = \exp(\alpha_e d)$ for $k_A = 0$ but $M = (1-\alpha_e d)^{-1}$ for $k_A = 1$.
  Avalanche breakdown occurs for $\alpha_e d = 1$.

Common APDs

Parameter	Symbol	Unit	Si	Ge	InGaAs
Wavelength	λ	μm	0.4–1.1	0.8–1.8	1.0–1.7
Responsivity	R_{APD}	A/W	80–130	3–30	5–20
APD gain	M	—	100–500	50–200	10–40
k-factor	k_A	—	0.02–0.05	0.7–1.0	0.5–0.7
Dark current	I_d	nA	0.1–1	50–500	1–5
Rise time	T_r	ns	0.1–2	0.5–0.8	0.1–0.5
Bandwidth	Δf	GHz	0.2–1	0.4–0.7	1–10
Bias voltage	V_b	V	200–250	20–40	20–30

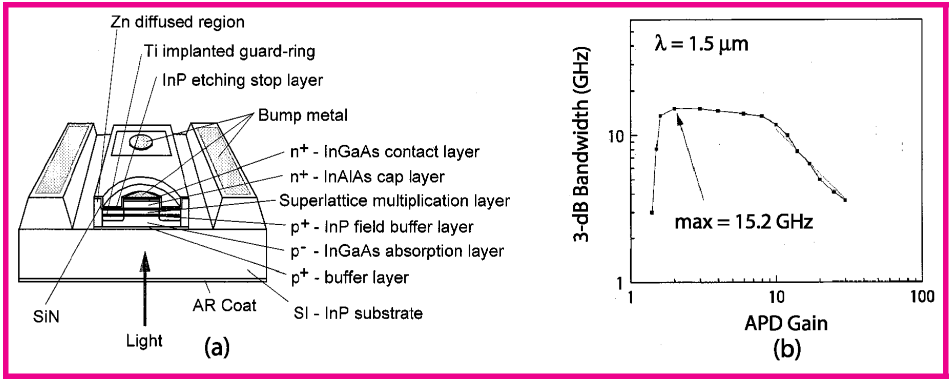
- Higher responsivity but more noisy. Require large bias.
- Smaller bandwidth: generation and collection of secondary e–h pairs take additional time: $M(\omega) = M_0[1 + (\omega \tau_e M_0)^2]^{-1/2}$.

Advanced APDs



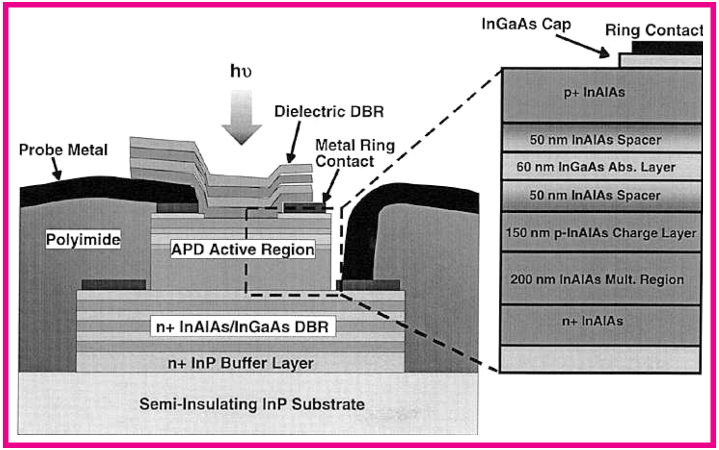
- SAM APDs: Separate absorption and multiplication regions. Gain layer is made of a non-absorbing semiconductor.
- SAGM: Separate absorp., grading and multiplication regions. Insert another layer between the absorption and multiplication regions with bandgap intermediate to those of InP and InGaAs layers.
- SAGCM: Absorp., grading, charge and multiplication regions. Insert a charge layer between the grading and multiplication regions.

Superlattice APDs



- InGaAs APDs: Comparable values of α_e and α_h.
- A superlattice design reduces the ratio α_h/α_e.
- Absorption and multiplication regions alternate and consist of thin layers (∼10 nm) of semiconductor materials with different bandgaps.
- Staircase APDs: InGaAsP layer compositionally graded to form a sawtooth structure that looks like a staircase under reverse bias.

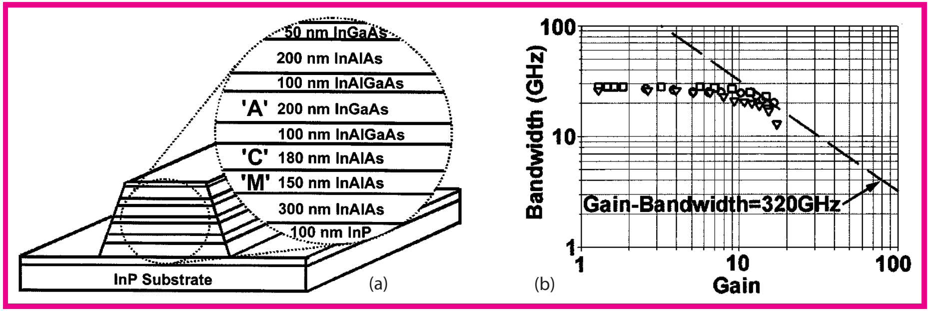
Resonant-Cavity APDs



- A Fabry–Perot cavity formed to enhance absorption within a thin layer through multiple round trips.
- Entire structure is placed between two distributed Bragg reflectors formed with multilayer stacks.
- Such a 1.55-μm APD exhibited 70% quantum efficiency.

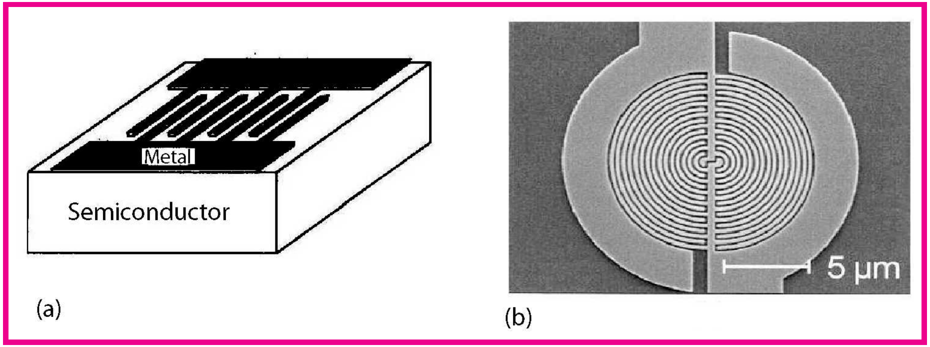
Back
Close

Resonant-Cavity APDs



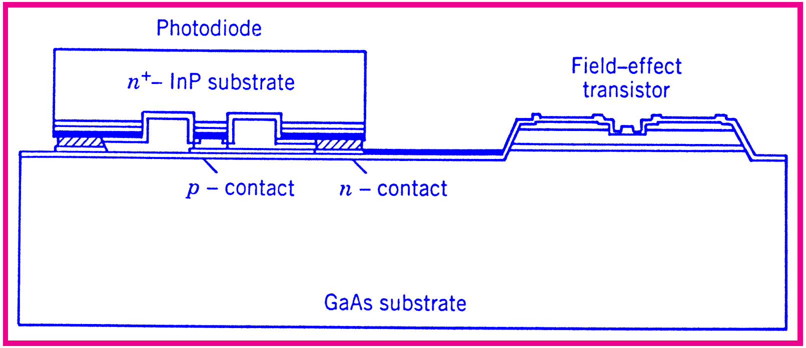
- Propagation inside a waveguide provides long absorption lengths.
- waveguide width 4–20 μm, length 10–100 μm.
- Required voltage across the thin waveguide smaller ($\sim$10 V).
- Bandwidth enhanced because of lower transit time ($\sim$1 ps).
- 3-dB bandwidth for a $10-\mu$m-wide waveguide was 28 GHz.
- Gain–bandwidth product was as large as 320 GHz.

MSM Photodetectors



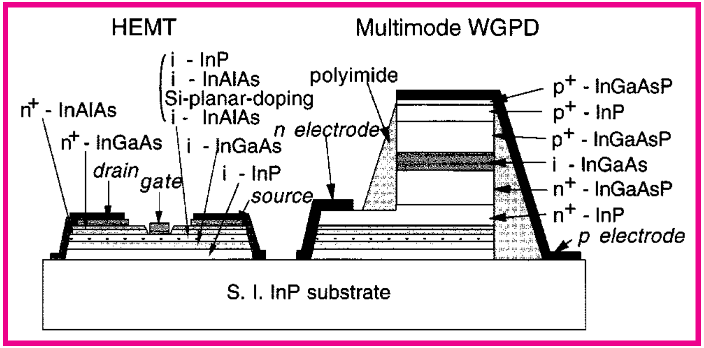
- A semiconductor layer sandwiched between two metal electrodes.
- A Schottky barrier formed at each metal–semiconductor interface.
- It prevents flow of electrons from metal to the semiconductor.
- In practice, two metal contacts are formed on the same side of absorbing layer using interdigited electrodes (finger spacing 1 μm).
- Such a structure exhibits low parasitic capacitance and allows high-speed operation (up to 300 GHz).

Optoelectronic Integration



- Relatively easy for GaAs receivers using GaAs-based ICs.
- A hybrid approach, called flip-chip technology, used for InP.
- Electronic components integrated on a GaAs chip.
- Photodiode made on top of an InP substrate.
- Two chips connected by flipping the InP chip on top of GaAs IC chip.

Optoelectronic Integration



- A receiver made by integrating a waveguide photodetector with an high-electron-mobility transistor on the same InP chip.
- By 2000, such receivers exhibited bandwidths of 45 GHz.
- All epitaxial layers grown on a semi-insulating InP substrate using the MOCVD technique.
- Ridge waveguide formed using reactive ion etching.
- Entire receiver chip 2.5 mm long and 1.2 mm wide.

WDM Components

- Wavelength-division multiplexing (WDM) extends the capacity of lightwave systems to >1 Tb/s.
- Multiple optical carriers spaced 50–100 GHz apart transmit data simultaneously over the same fiber.
- Many waveguide-based passive and active components developed for WDM systems.
  - ⋆ Tunable optical filters for channel selection
  - ⋆ Multiplexers and demultiplexers combining channels
  - ⋆ Add–drop multiplexers for adding or dropping a channel
  - ⋆ WDM transmitters and receivers

Tunable Optical Filters

- Desirable properties: wide tuning range, negligible crosstalk, fast tuning speed, small insertion loss, insensitivity to signal polarization, low cost, stability against environmental changes.

- An optical filter is characterized by its transfer function $H_f(\omega)$:

$$A_{\text{out}}(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} H_f(\omega)\tilde{A}_{\text{in}}(\omega)\exp(-i\omega t)\,d\omega.$$

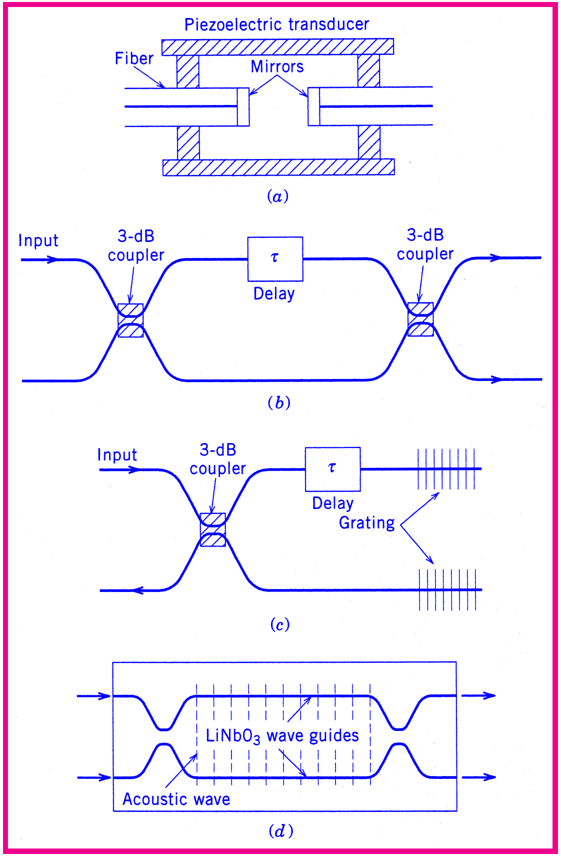
- We can write $H_f(\omega)$ as

$$H_f(\omega) = |H_f(\omega)|e^{i\phi(\omega)} \approx |H_f(\omega)|\exp[i(\phi_0 + \phi_1\omega + \tfrac{1}{2}\phi_2\omega^2 + \cdots)].$$

- Constant ϕ_0 can be ignored; ϕ_1 introduces a time delay; ϕ_2 governs dispersive properties of an optical filter.

Designs of Optical Filters

- Fabry–Perot filter
- Mach–Zehnder filter
- Michelson filter
- Acousto-optic filter



Back
Close

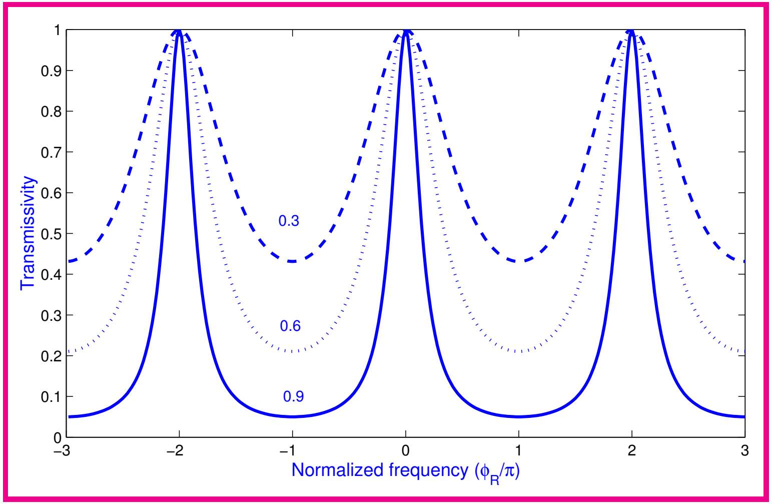
Fabry–Perot Filters

- Consist of a cavity formed with two high-reflectivity mirrors.
- In a common design, two fiber ends are coated to form mirrors, and air gap between fibers acts as a cavity.
- Filter tuned by changing the width of air gap electronically using a piezoelectric transducer.
- Transfer function of an FP filter with mirror reflectivity R_m:

$$H_f(\omega) = \frac{(1-R_m)e^{i\pi}}{1-R_m\exp(i\omega\tau_r)}.$$

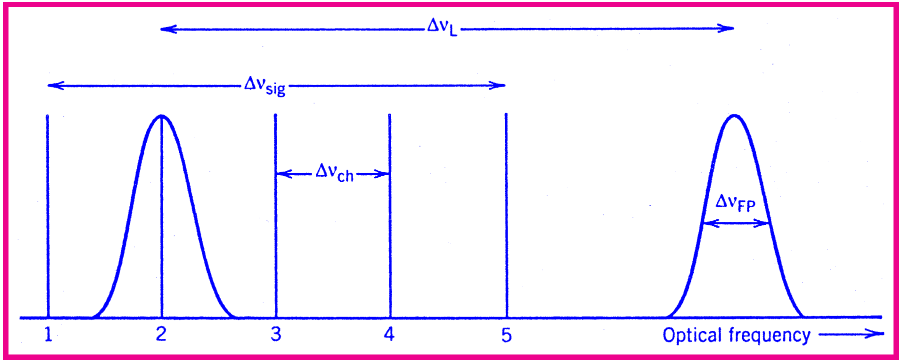
- $\tau_r = 2L_f/v_g$ = round-trip cavity time.
- Condition $\omega\tau_r = 2\pi m$ determines longitudinal modes of FP filter.

Transfer Function of FP Filters



- Transmissivity becomes maximum when frequency ν coincides with a longitudinal mode of the resonator ($\nu = \nu_m = m/\tau_r$).
- Spacing between peaks governed by free spectral range related to round-trip time τ_r as $\Delta\nu_L = 1/\tau_r = v_g/(2L_f)$.
- Length L_f is controlled electronically to tune the filter.

WDM Channel Selection



- Combined bandwidth of the WDM signal, $\Delta\nu_{\text{sig}} = N\Delta\nu_{\text{ch}} = NB/\eta_s$, must be less than $\Delta\nu_L$.
- $\Delta\nu_{\text{ch}}$ = channel spacing, $\eta_s = B/\Delta\nu_{\text{ch}}$ = spectral efficiency.
- Filter bandwidth $\Delta\nu_{\text{FP}}$ should be large enough to pass the entire channel ($\Delta\nu_{\text{FP}} = B$).
- These two conditions limit N to $N < \eta_s(\Delta\nu_L/\Delta\nu_{\text{FP}}) = \eta_s F_R$, where $F_R = \Delta\nu_L/\Delta\nu_{\text{FP}}$ is the finesse.

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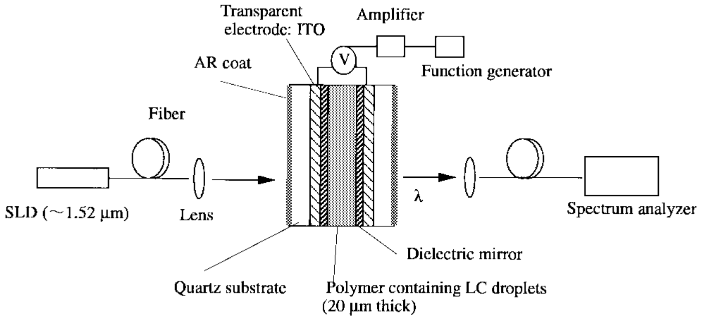
Liquid-Crystal FP Filters

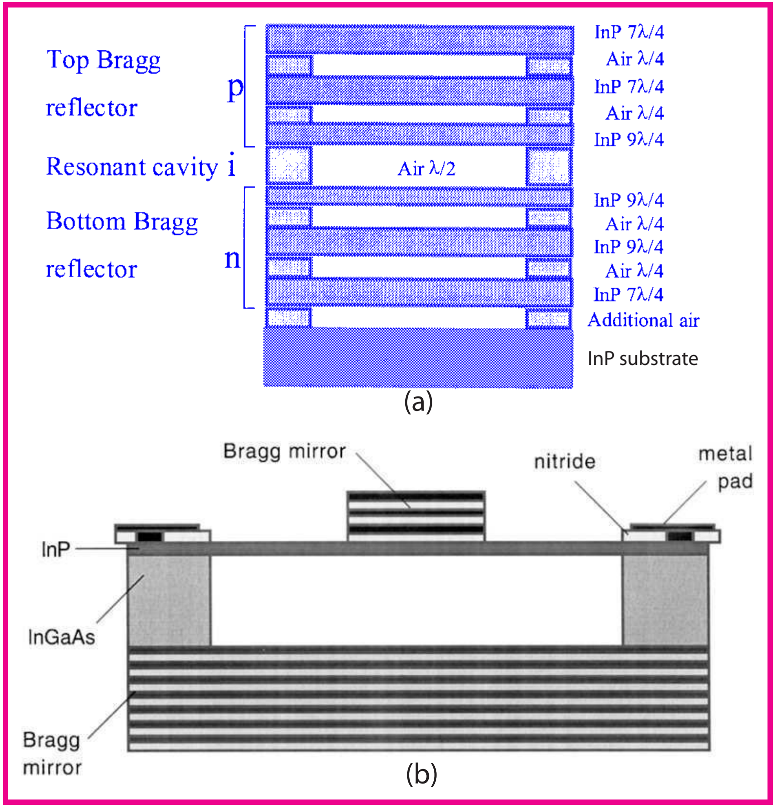
- Rather then changing the physical length, refractive index is changed electronically to tune the filter.
- Such FP filters can provide high finesse ($F_R \sim 300$) with a narrow bandwidth (about 0.2 nm).
- Tunable over 50 nm; Time $\sim$1 ms for nematic liquid crystals.
- Switching time can be reduced to 10 μs with smectic liquid crystals.
- Liquid-crystal filters suffer from polarization sensitivity.
- Problem solved in practice using a polarization-diversity technique.
- Input field separated into two orthogonally polarized branches and recombined at the output end.

Liquid-Crystal FP Filters



- In a simpler approach, nanometer-size droplets of a liquid crystal (diameter <100 nm) were used.
- Mirrors made by coating two quartz plates with a thin film of indium-tin oxide; same film acts as a transparent electrode.
- Droplets formed by exposing liquid-crystal film containing a UV-curable polymer to intense UV light.
- Polarization insensitivity results from random orientation of droplets.

Interference Filters



Interference Filters

- Two thin-film mirrors are separated by a spacer layer (can be air) to form an FP cavity.
- In one design, a $\lambda/2$ air gap is surrounded by two distributed Bragg reflectors (DBRs).
- Normally, one needs more than 40 alternating layers for forming a high-reflectivity DBR.
- The number of layers reduced to just a few when InP layers were alternated with $\lambda/4$-thick air gaps.
- A 5-layer DBR shown can provide 99.6% reflectivity over a 230-nm bandwidth.

Interference Filters

- Such a FP filter exhibited a tuning range of 62 nm with 0.6-nm bandwidth and 14 V applied voltage.
- In another design, top Bragg mirror was suspended on four cantilever beams.
- Bragg mirror could be moved by 50 nm through electrostatic attraction.
- By 2003, such micromachined FP filters provided a tuning range of 140 nm with a voltage of only 3.2 V.

Mach–Zehnder Filters

- A MZ filter can be made with two directional couplers.
- First coupler splits input signal into two parts, which acquire different phase shifts before they interfere at the second coupler.
- Since relative phase shift in two arms is wavelength-dependent, transmission depends on the signal wavelength.
- Transfer function for the bar and cross ports:

$$
\begin{aligned}
H_b(\omega) &= \sqrt{\rho_1\rho_2}\exp(i\omega\tau) + i^2\sqrt{(1-\rho_1)(1-\rho_2)} \\
H_c(\omega) &= i\sqrt{\rho_1(1-\rho_2)}\exp(i\omega\tau) + i\sqrt{\rho_2(1-\rho_1)}
\end{aligned}
$$

- Extra delay in one arm of MZ filter $\tau = n_f \Delta L/c$ plays an important role.

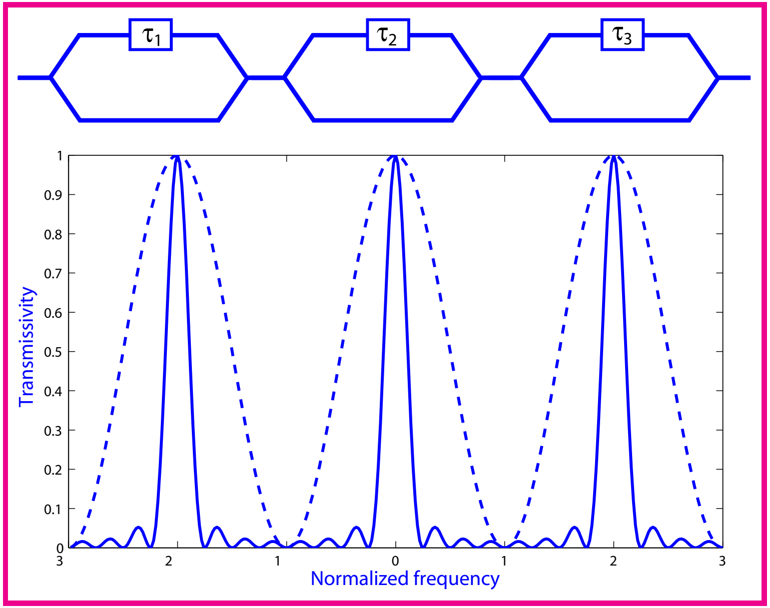
Mach–Zehnder Filters

- For MZ filters made with two 3-dB couplers ($\rho_1 = \rho_2 = \frac{1}{2}$):

$$|H_b(\omega)|^2 = \sin^2(\omega\tau/2), \qquad |H_c(\omega)|^2 = \cos^2(\omega\tau/2).$$

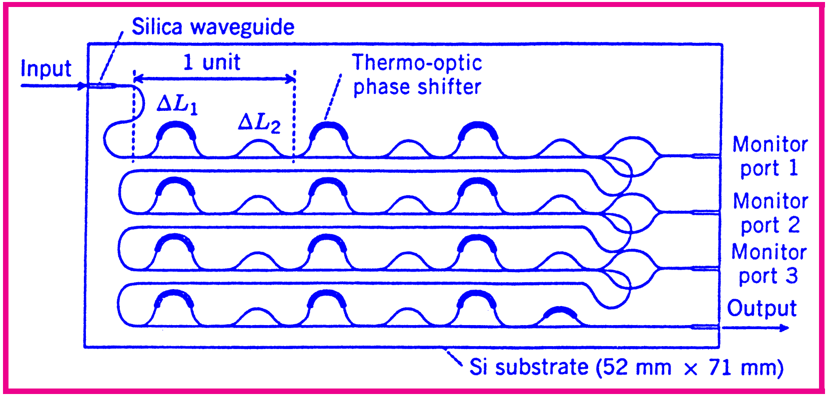
- When Y-junction couplers are used, MZ filter has single input and output ports.
- In this case, transfer function is given by $|H_f(\omega)|^2 = \cos^2(\omega\tau/2)$.
- Such a filter is not sharp enough for WDM systems.
- Better spectral response realized by cascading several MZ interferometers in series.
- When only 3-dB couplers are used, $|H_f(\omega)|^2 = \prod_{m=1}^{M} \cos^2(\omega\tau_m/2)$.
- Extra delay τ_m in each MZI used to control filter characteristics.

Cascaded Mach–Zehnder Interferometers



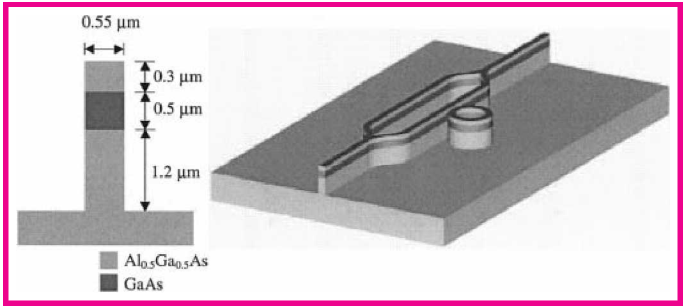
- Transfer function for $M = 3$ with the choice $\tau_1 = \tau,\ \tau_2 = 2\tau$, and $\tau_3 = 4\tau$.
- When $\tau_m = (2^m \Delta\nu_{ch})^{-1}$, each MZ blocks alternate channels.

Cascaded Mach–Zehnder Interferometers



- Planar lightwave circuits made with silica-on-silicon technology.
- Filter characteristics can be controlled by changing the arm lengths and the number of MZ interferometers.
- A chromium heater deposited on one arm of MZ interferometers to provide thermo-optic control of optical phase.
- Switching time is ∼1 ms because of a thermal tuning mechanism.

Other Designs for MZ Filters

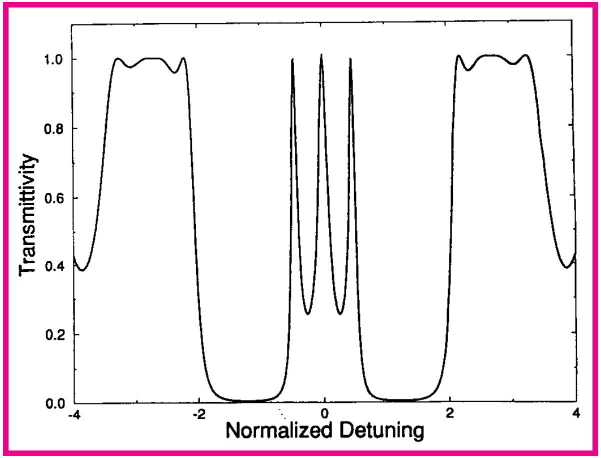


- Faster tuning possible with $LiNbO_3$ or GaAs waveguides.
- Refractive index in one arm changed electronically.
- Semiconductor waveguides grown on GaAs or InP substrates are often employed.
- A GaAs-based notch filter with a microring in one arm.
- MZ arms separated by 10 μm and <0.1 mm long.
- Transmission drops to zero periodically at cetain frequencies.

Bragg-Grating Filters

- A fiber grating acts as a narrowband reflection filter.
- Central wavelength determined by the Bragg wavelength $\lambda_B = 2\bar{n}\Lambda$, where $\bar{n}$ is mode index.
- Several schemes use fiber gratings to make transmission filters.
- Two Fiber gratings can be used as mirrors of a FP filter.
- Bragg gratings in each arm of a MZ interferometer also separate reflected channel from the input signal.
- Such a device acts as a Michelson interferometer built with two wavelength-selective mirrors.

Phase-Shifted Bragg-Grating Filters



- A $\pi/2$ phase shift in the middle of grating opens a narrow transmission peak within the stop band of the grating.
- It is possible to open multiple transmission peaks by creating multiple phase shift regions along the length of a grating.
- Three transmission peaks occur when $\pi/2$ phase shift regions are spaced apart by $L_g/4$ along the grating length.

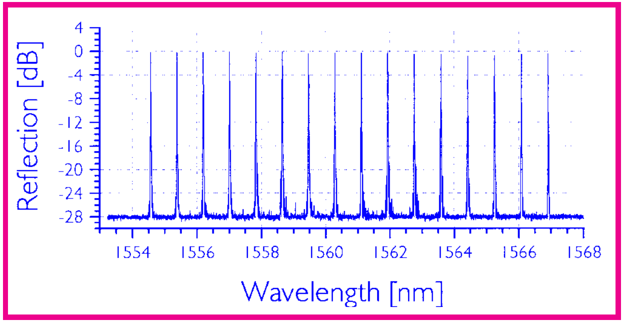
Sampled-Grating Filters

- A Bragg filter does not have a periodic transfer function.
- This property can be changed by employing a sampled grating.
- Coupling coefficient κ modulated in a periodic fashion.
- Such devices are made by placing an amplitude mask before UV light creates interference pattern.
- κ alternates between 0 and a finite value along grating length.
- Refractive index varies as $n(z) = \bar{n} + \mathrm{Re}[\delta n_1(z)\exp(2\pi i z/\Lambda)]$.
- Since $\delta n_1(z)$ is periodic, we expand it in a Fourier series:

$$n(z) = \bar{n} + \mathrm{Re}\left(\sum_m F_m \exp[2i(\beta_B + m\beta_s)z]\right),$$

- $\beta_B = \pi/\Lambda$ and $\beta_s = \pi/\Lambda_s$.

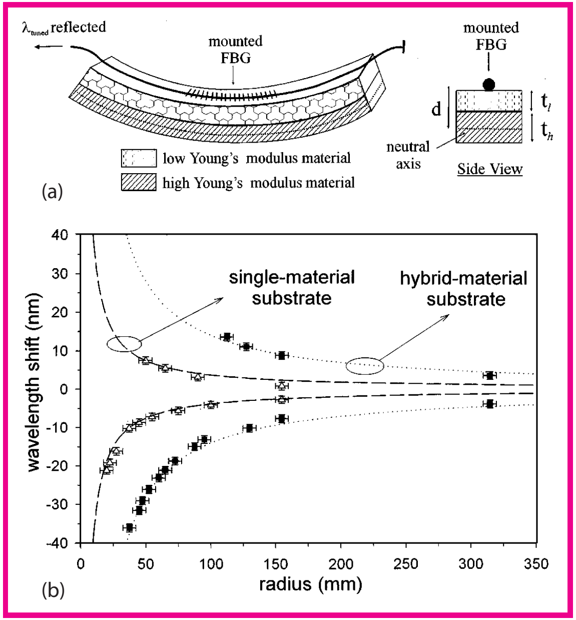
Sampled-Grating Filters



- Sampling period Λ_s determines periodicity of reflection peaks.
- Frequency spacing $\Delta\nu = c/(2\bar{n}\Lambda_s) = 100$ GHz for $\Lambda_s \approx 1$ cm.
- Sampled gratings have evolved considerably in recent years.
- Basic idea: Choose $\delta n_1(z)$ to tailor transmission characteristics of a sampled grating.
- A "sinc" function for $\delta n_1(z)$ produces rectangular passbands.
- Phase-sampled gratings provide even better performance.

Tuning of Grating Response

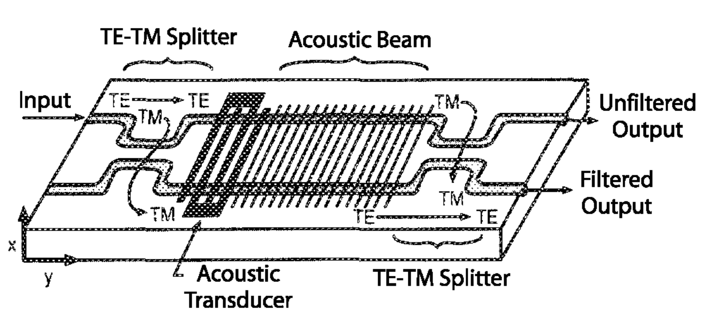
- Spectral response tuned by stretching or compressing the grating.
- Grating mounted on a hybrid substrate.
- Tuning range of 90 nm realized.
- Thermo-optic effect can also be used for tuning.
- Bragg wavelength shifts at a rate of 10 pm/°C.



Acousto-Optic Filters

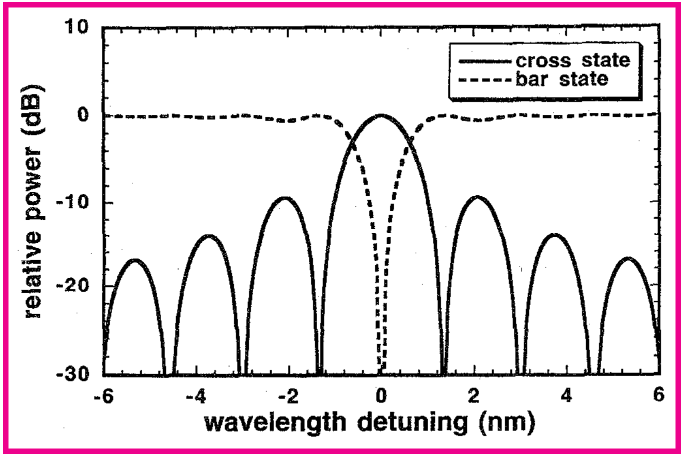
- Grating formed using a high-frequency acoustic wave.
- Acoustic wave creates a refractive-index grating through the photoelastic effect.
- Grating diffracts incident optical beam when the Bragg condition is satisfied.
- Such filters can be made by using bulk components as well as planar waveguides.
- In both cases, a piezoelectric transducer is used to generate the acoustic wave.
- Use of $LiNbO_3$ waveguides provides compact filters.

Waveguide Acousto-Optic Filters



- TE and TM components are processed separately.
- All components can be integrated on the same $LiNbO_3$ substrate.
- TE–TM mode conversion by acoustic wave when Bragg condition $\beta_{\rm TM} - \beta_{\rm TE} = 2\pi/\Lambda_a$ is satisfied.
- Using $\Lambda_a = \lambda/(\Delta n)$ with $\Delta n \approx 0.07$, $\Lambda_a = 22\ \mu$m and $\nu_a = 170$ MHz for $\lambda = 1.55\ \mu$m.

Transfer function

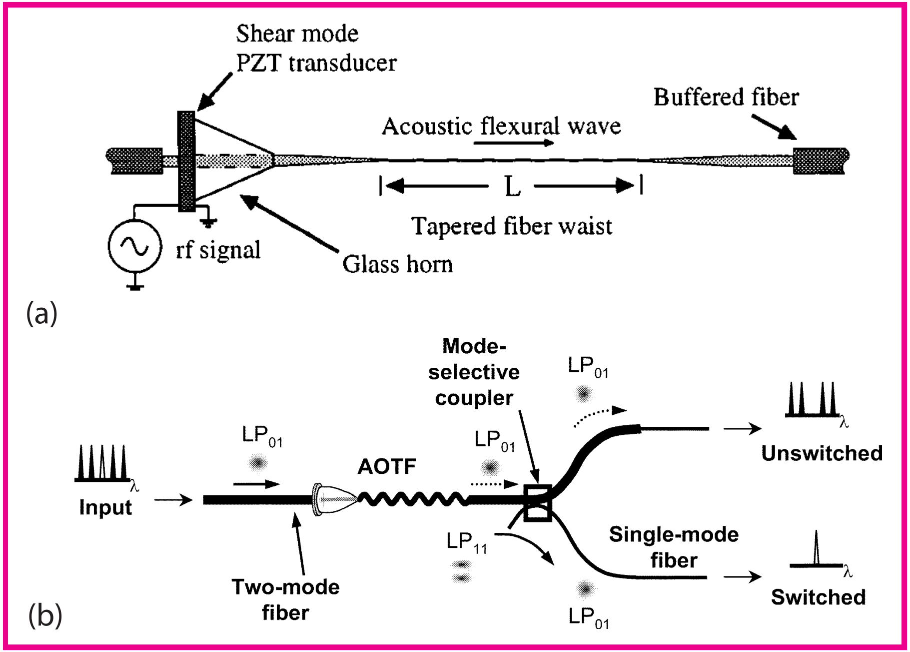


- Transfer function of an acousto-optic filter exhibits side lobes.
- 3-dB Filter bandwidth is typically <0.5 nm.
- Passband can be flattened through suitable design modifications.
- Tuning range 40 nm; insertion losses ~4 dB.

Fiber-Based Acousto-Optic Filters

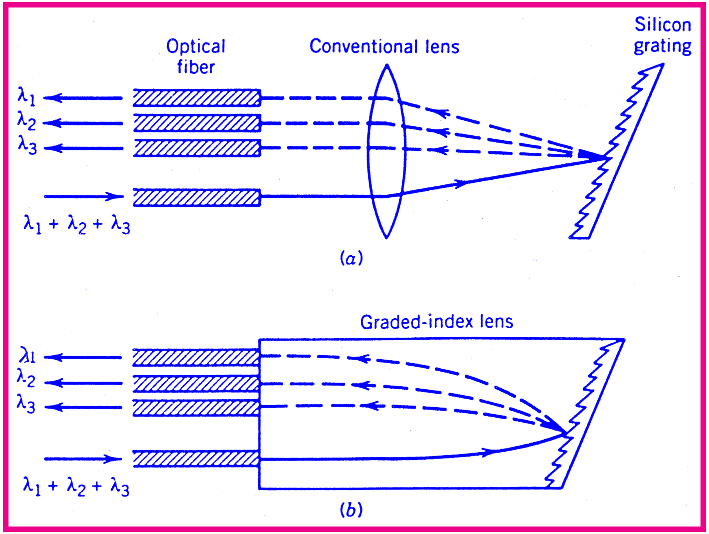
- Coupling losses can be avoided with an all-fiber approach.
- Basic idea: Couple two modes of the fiber through acoustically induced index grating.
- A piezoelectric transducer produces acoustic vibrations that are amplified and transmitted to the optical fiber using a horn.
- A specific wavelength is selectively transferred to the higher-order mode.
- A mode-selective coupler used to separate filtered channel.

Fiber-Based Acousto-Optic Filters



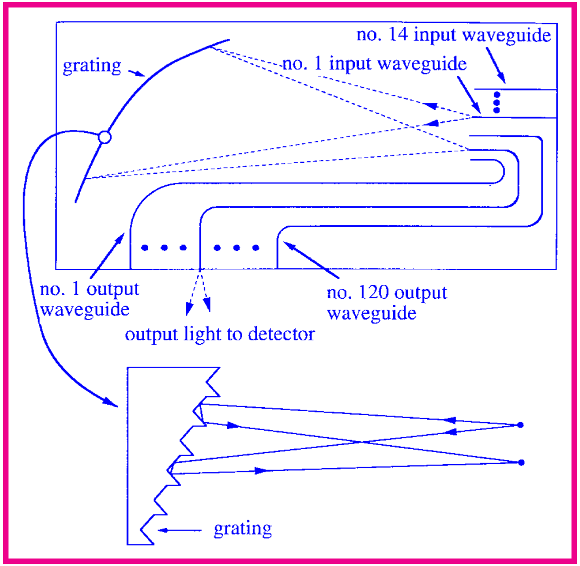
- Two schemes baed on (a) tapered fiber; (b) two-mode fiber.

Grating-Based Demultiplexers



- Demultiplexers contain a wavelength-selective element to separate individual channels of a WDM signal.
- Grating-based demultiplexers use diffraction from an optical grating.
- Focusing lens can be replaced with a graded-index lens.

Grating-Based Demultiplexers



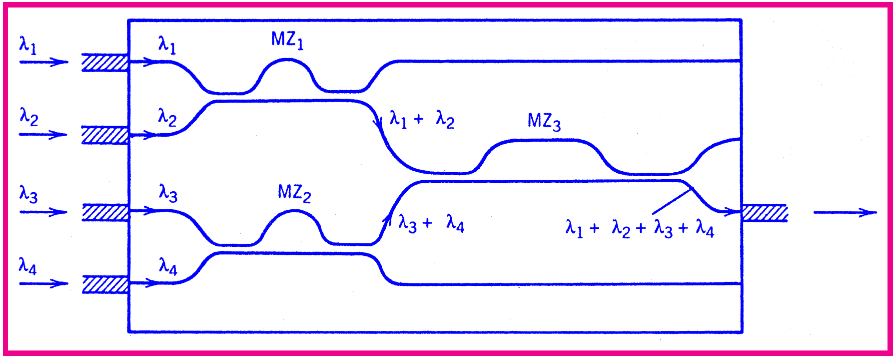
- A concave grating etched directly onto a silica waveguide.
- Input and output waveguides integrated on the same substrate.
- Entire chip was 1 cm wide and 3.4 cm long.

- Main drawback: Relatively large insertion loss (>20 dB).

Back

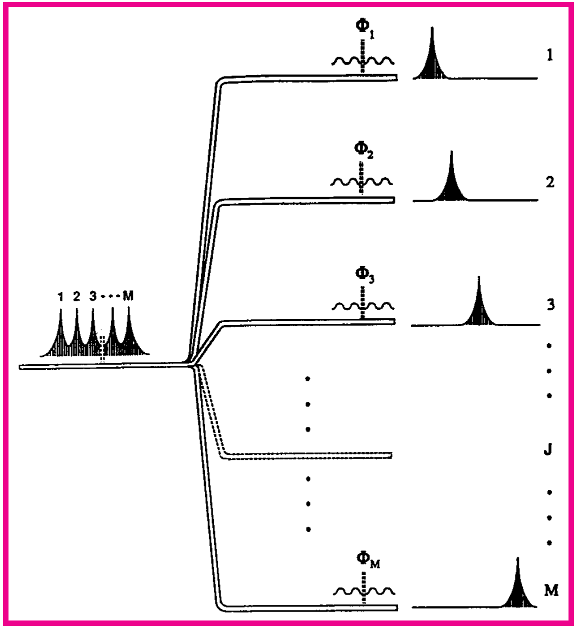
Close

Filter-Based Demultiplexers



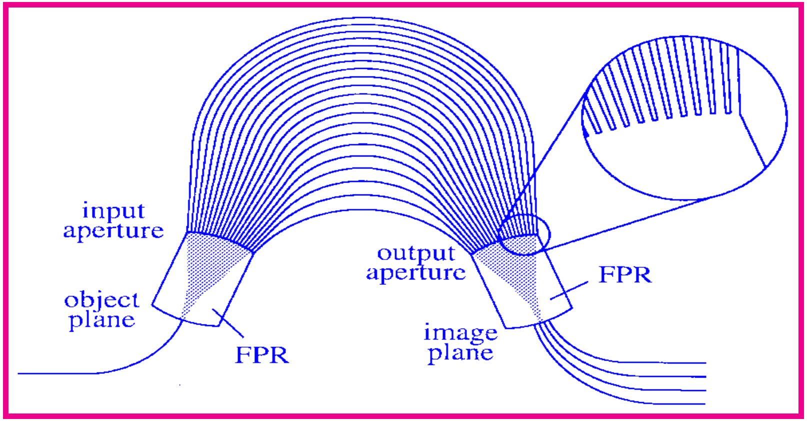
- Use MZ interferometers to multiplex WDM channels.
- Path-length difference is chosen such that incoming power from two ports appears at the same output port.
- Same device works as a demultiplexer when a WDM signal is launched from the right end.
- Whole structure can be fabricated on a silicon substrate using SiO_2 waveguides (a planar lightwave circuit).

Fiber-Based Demultiplexers



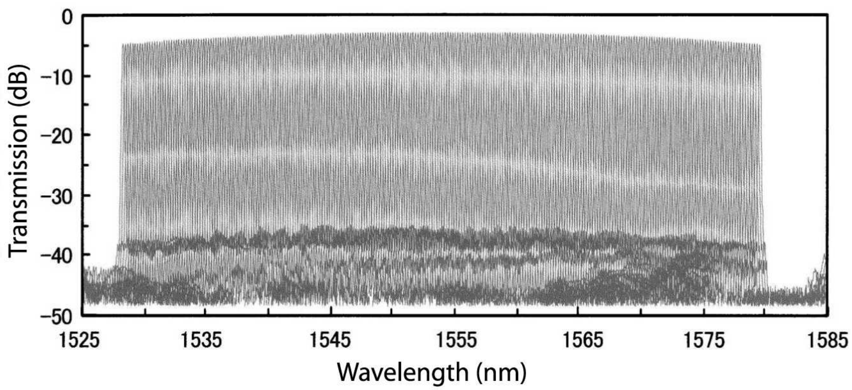
- A $1 \times N$ fiber coupler converted into a demultiplexer with a phase-shifted grating at the end of each output port.
- Amount of phase shift varied to select the channel.

Waveguide-Grating Demultiplexers



- A phased array of optical waveguides acts as a grating.
- Two star couplers at two ends act as lenses.
- Different channels focus to different output waveguides.
- Integrated version of two lenses and a bulk grating.
- Such devices are fabricated with silica-on-silicon technology.

Waveguide-Grating Demultiplexers



- Transmission spectra of an AWG demultiplexer designed for separating 256 channels with 25-GHz spacing.
- AWG contaied 712 waveguides whose length increased by 27.7 μm.
- Chip size was only 7.5×5.5 cm^2.
- Insertion losses ranged from 2.7 to 4.7 dB.

Optical Add–Drop Multiplexers

- OADMs are needed for all-optical networks in which WDM channels are maintained in the optical domain at intermediate nodes.
- A specific channel at a certain wavelength is dropped or added, while preserving the integrity of all other channels.
- Such a component differs from optical filters.
- OADMs need four ports, in contrast with optical filters that have only two ports.

Directional Couplers with Gratings

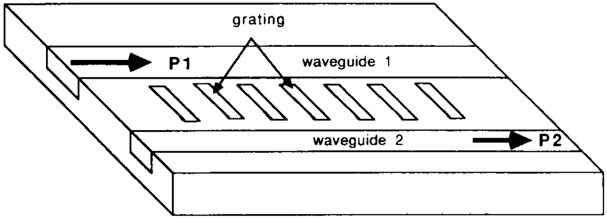
- Bragg grating fabricated in one or both cores of a coupler.
- Grating is designed to assist or frustrate coupling between two cores for a specific channel.
- In a grating-frustrated coupler, two cores are identical and light is transferred to neighboring core in the absence of grating.
- Grating frustrates the transfer of a channel whose wavelength falls within its stop band.
- This channel remains in the same core and appears at the bar port of the coupler (dropped channel).
- A channel at the same wavelength can be added by injecting it from the unused input port.

Grating-Assisted Directional Couplers

- In a grating-assisted coupler, two cores are made dissimilar.
- No power transfer between two core occurs without grating.
- Grating occupies the second core and helps to transfer a specific channel to the other core.
- If a long-period grating is used, dropped channel appears at the cross port.
- A short-period Bragg grating not only couples light into second core but also reflects it.
- Dropped channel appears then appears at the 2nd port on the input side.

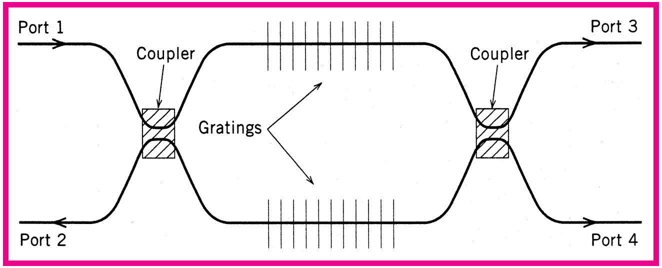
Back
Close

Grating-Assisted ADM



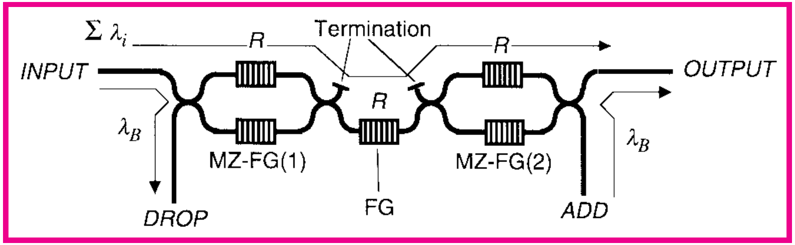
- In another scheme, two cores are made identical.
- Bragg Grating is fabricated in the central coupling region.
- All channels cross over to the second core.
- Channel whose wavelength falls within the stop band of the grating is reflected by the grating and travels in the backward direction.
- This channel appears at the second input port.

Mach–Zehnder Interferometer with Gratings



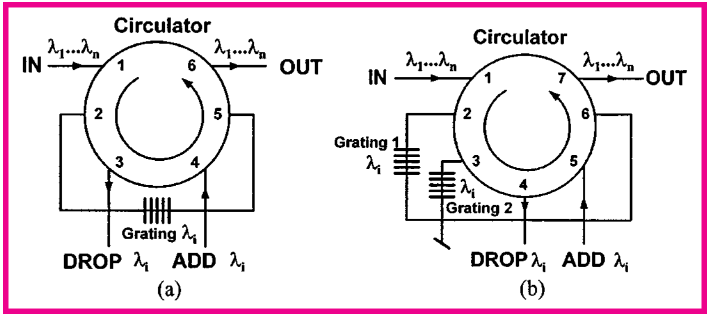
- Bragg grating is design to reflect a specific channel.
- This channel appears at port 2; remaining channels go to port 4.
- Channel to be added is injected from port 3.
- Grating should be 100% reflecting to minimize crosstalk.
- MZ interferometer should be perfectly balanced for such OADMs.
- UV trimming is used in practice to ensure equal phase shifts in two arms of the MZ interferometer.

Cascaded Mach–Zehnder OADMs



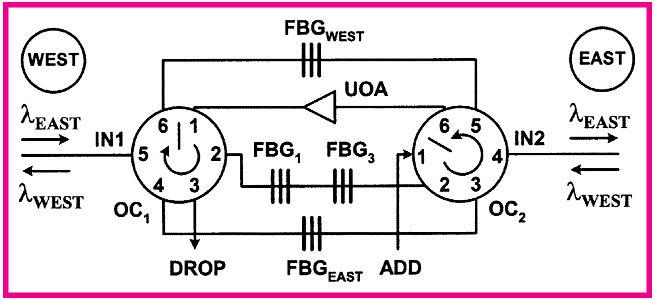
- For WDM applications, a crosstalk level of -20 dB is not sufficient.
- It can be reduced to below -40 dB by cascading two OADMs in series.
- First OADM drops off channel at λ_B.
- Any power leaked through the first OADM is reflected by the middle fiber grating before WDM signal enters second OADM.
- Two gratings in this section further reduce the power at λ_B before the new signal is added.

Optical Circulator with Gratings



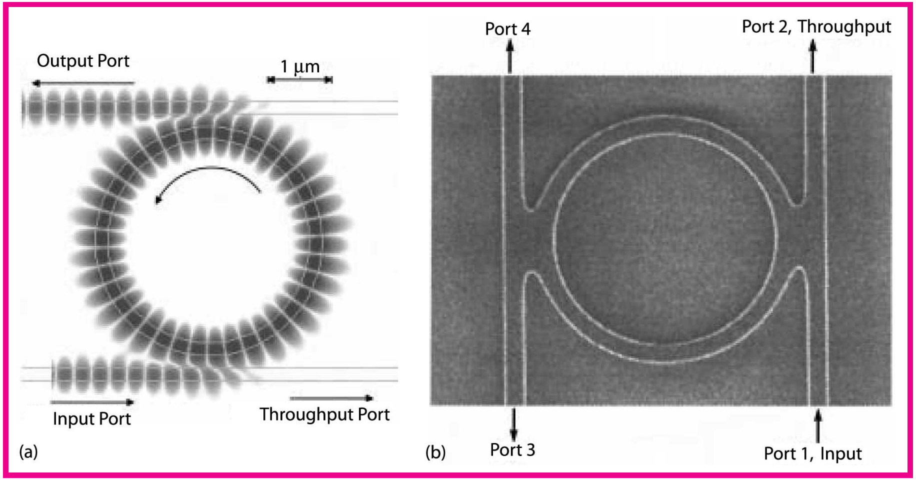
- OADMs can be made using two 3-port optical circulators.
- To reduce insertion losses, use of a single optical circulator is better.
- OADM designs with a single circulator and fiber gratings.
- In design (a), dropped channel appears at port 3.Channel to be added enters from port 4.
- Crosstalk can be reduced by employing two gratings as shown in design (b).

Bidirectional OADM



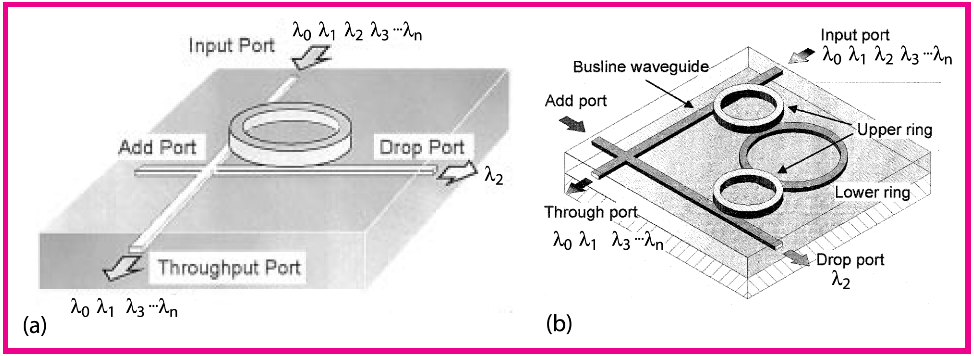
- Constructed by combining two circulators with multiple Bragg gratings.
- One can even insert an optical amplifier to amplify channels before adding and dropping.
- Gratings marked FBG$_{\text{EAST}}$ and FBG$_{\text{WEST}}$ reflect WDM signals traveling in the east and west directions.
- Gratings marked FBG$_1$ and FBG$_3$ reflect channels that need to be dropped (or added) in the east and west directions.

Microring Resonators



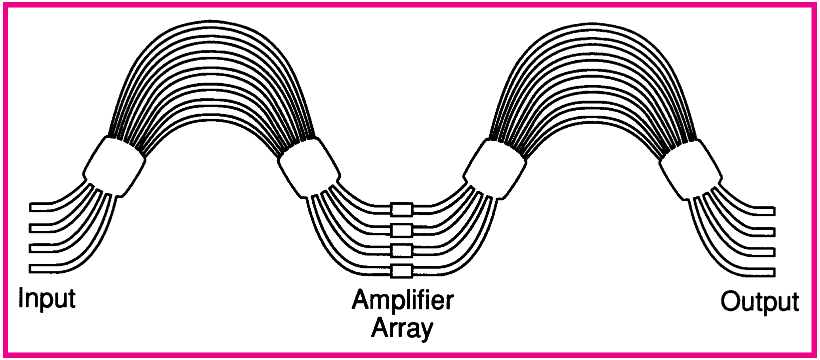
- Channel whose wavelength coincides with a longitudinal mode of the microring is transferred to the upper waveguide (and dropped).
- Remaining channels stay in the first waveguide.
- Such an OADM can be fabricated with silica or polycrystalline silicon waveguides.

Microring Resonators



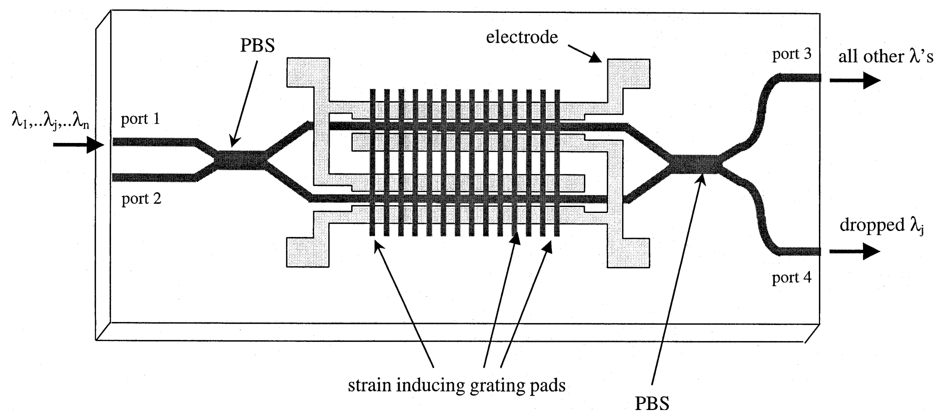
- Two schemes for coupling a microring to linear waveguides vertically.
- Two waveguides do not have to be parallel.
- Three-ring design provides larger free spectral range and higher finesse; it is used to tailor shape of resonance peak.
- Resonance bandwidth of <0.5 nm, a free spectral range of $>$10 nm, and a finesse of $>$1,000 possible.

Tunable Add–Drop Multiplexers



- First AWG separates WDM channels and directs them to different ports.
- Amplifier gains adjusted to amplify only the channel to be dropped.
- Second AWG multiplexes all channels so that the dropped channel appears at a specific port (other channels lost because of loses).
- Channels can be added using Y-junction couplers at the input end of amplifiers.

$LiNbO_3$-Based Tunable OADM



- A rapidly tunable OADM can be made using two $LiNbO_3$ waveguides processing the TE and TM components separately.
- Index grating created by applying strain along the waveguide length in a periodic fashion.
- A SiO_2 film deposited on top of waveguides and metal contacts placed with a fixed spatial period.

Back
Close

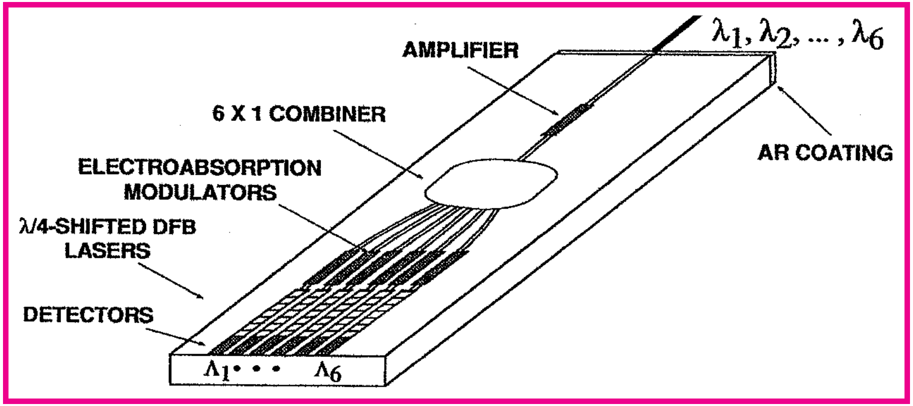
Tunable OADMs

- Strain results from thermal-expansion mismatch between the substrate and film.
- Tuning is realized by changing the Δn in the Bragg condition $\lambda_d = \Lambda |\Delta n|$.
- Silica-on-silicon technology also permits tuning of an OADM but it relies on the relatively slow thermo-optic effect.
- Device consists of cascading several asymmetric MZ interferometers with a built-in chromium heater in one arm of each MZ.
- Relative phase shift between the two arms can be altered by changing the refractive index in one of the arms thermally.
- This change allows one to tune the wavelength of the channel that should be dropped or added by the device.

WDM Transmitters and Receivers

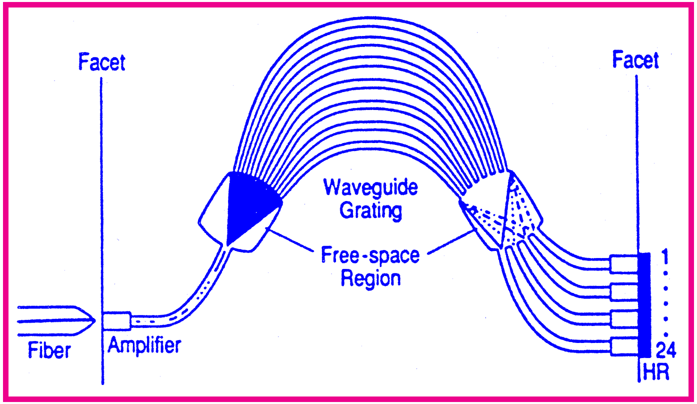
- WDM systems require one DFB laser for each channel.
- Laser wavelengths for two neighboring channels should differ by a precise amount to produce channel spacing (50–100 GHz).
- Laser wavelengths must fall on the ITU grid.
- Use of individual transmitters for each channel becomes impractical when the number of channels becomes large.
- Use of tunable semiconductor lasers reduces inventory and maintenance problems.
- Multiwavelength transmitters provide an alternative solution to this problem.

Optoelectronic Integrated Circuits



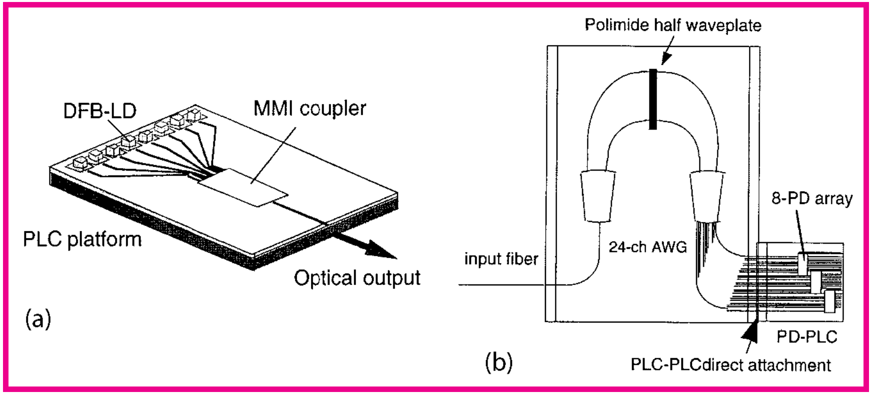
- Transmitter made by integrating multiple DFB lasers, electro-absorption modulators, and back-facet detectors.
- Output of all lasers combined and amplified on the same chip.
- Up to 16 DFB have been integrated with this technique.

WDM Transmitters with an AWG



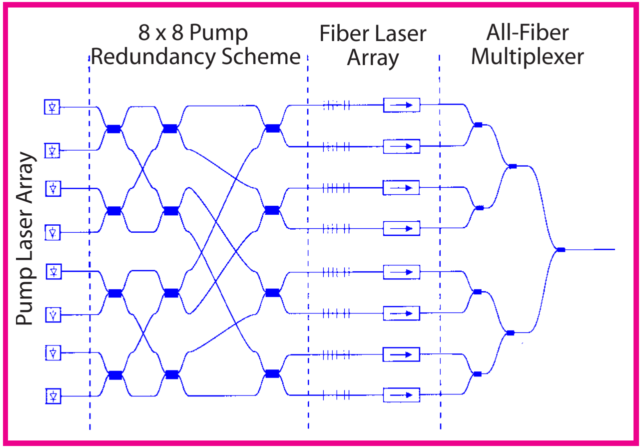
- WDM transmitter made by integrating an AWG inside laser cavity.
- Spontaneous emission of left amplifier is demultiplexed into multiple spectral bands through spectral slicing.
- Amplifier array on the right amplifies this set of wavelengths.
- By 1999, WDM transmitter with up to 40 wavelengths were made.

Hybrid Integration



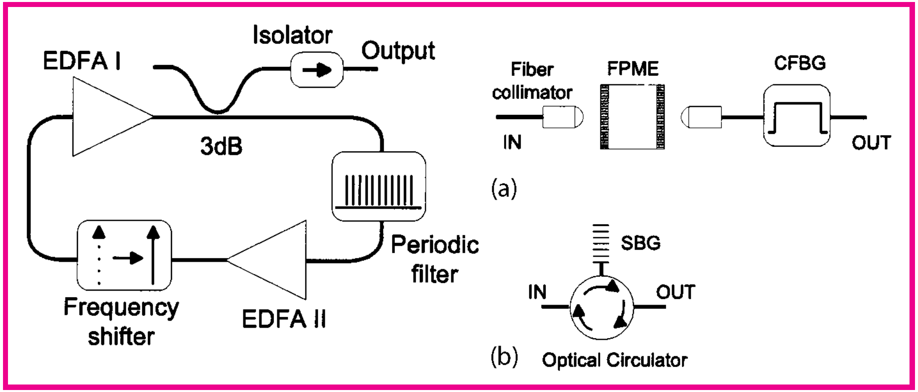
- Multiple lasers fabricated on an InP substrate.
- Laser outputs combined using a photonic lightwave circuit made with silica-on-silicon technology.
- Channels can be multiplexed using an MMI coupler.
- A similar scheme can be used for WDM receivers; micromirrors used to reflect signal toward a photodiode array.

Fiber-Laser Transmitters



- Twelve 3-dB couplers combined such that each laser pumps all DFB fiber lasers.
- Such a pumping scheme provides redundancy against pump failure.
- Outputs of 8 lasers combined using an all-fiber multiplexer.
- Measured intensity noise low because of power averaging.

Fiber-Lasers Transmitters

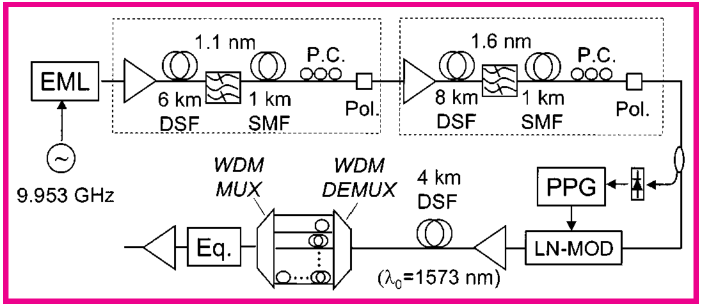


- Ring fiber lasers can emit light at multiple wavelengths.
- Cavity contains a frequency shifter and an optical filter with multiple peaks (FP filter or a sampled grating).
- Frequency shifter (an acousto-optic modulator) shifts frequency by 100 MHz or so and forces laser to perate over a wide bandwidth.
- Filter selects a comb of frequencies chosen to coincide with ITU grid.

Fiber-Laser Transmitters

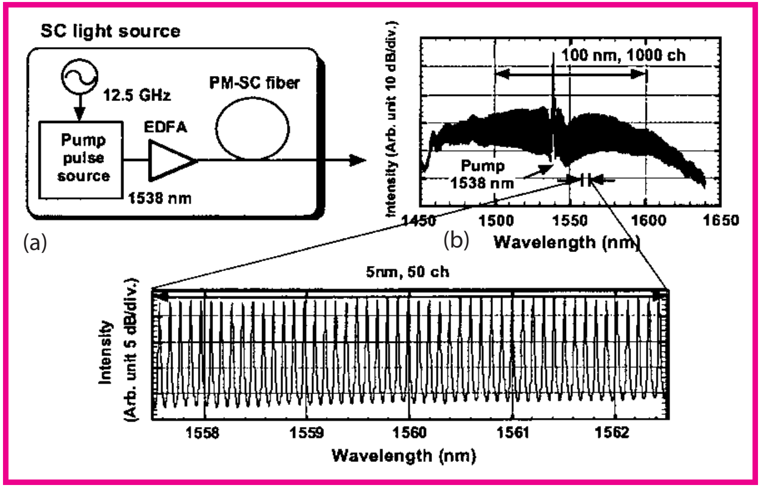
- Filter can be designed using several different techniques.
- In design (a), a FP filter is combined with a chirped fiber grating.
- Grating limits the spectral band over which the FP filter provides transmission.
- In design (b), a sampled fiber grating is used in combination with an optical circulator.
- An AWG can also be used for this purpose.
- WDM transmitters emitting light at 16 distinct wavelengths have been made with this technique.
- Semiconductor optical amplifier can be used in place of EDFA.
- A fiber-ring laser containing two SOAs and a fiber FP filter provided output at 52 channels with 50-GHz spacing.

Spectrally Sliced WDM Transmitters



- Output of a wide-bandwidth source is sliced spectrally.
- Picosecond pulses broadened spectrally to 200 nm through supercontinuum generation.
- Mod-locked laser (EML) generates 21-ps pulses at 10 GHz.
- Pulses amplified, chirped through SPM in a DSF, and compressed to 2.7 ps using a SMF.
- Pulses launched into 4-km-long DSF to produce supercontinuum.

Spectrally Sliced WDM Transmitters



- 1,000-channel source realized with 2.5-GHz channel spacing.
- 4.3-ps pulses amplified by an EDFA and then broadened spectrally in a polarization-maintaining fiber.
- Supercontinuum not required if femtosecond pulses are used.
- Spectral slicing of chirped-pulse spectrum provides WDM channels.

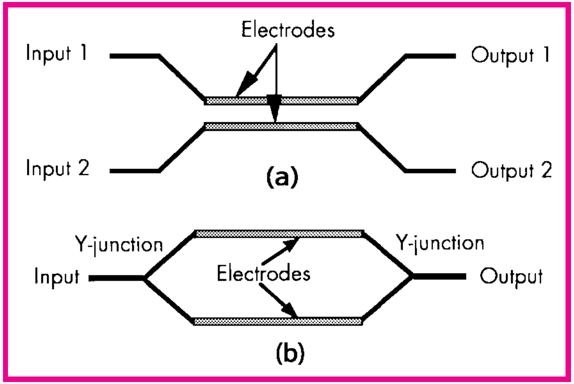
Optical Switching

- All-optical networks require switching of information optically, rather than electronically.
- Several kinds of optical switches have been developed.
- Some function in space domain such that entire channel is routed to the same output port (circuit switching).
- Others operate in time domain and can route individual bits or packets to different destinations (packet switching).
- This chapter focuses on space-domain switching schemes. Topics covered include wavelength routers, wavelength converters, and optical cross-connects.
- Space-domain switching requires devices that can direct their input to different output ports depending on an electric signal.

Y-Junction Switch

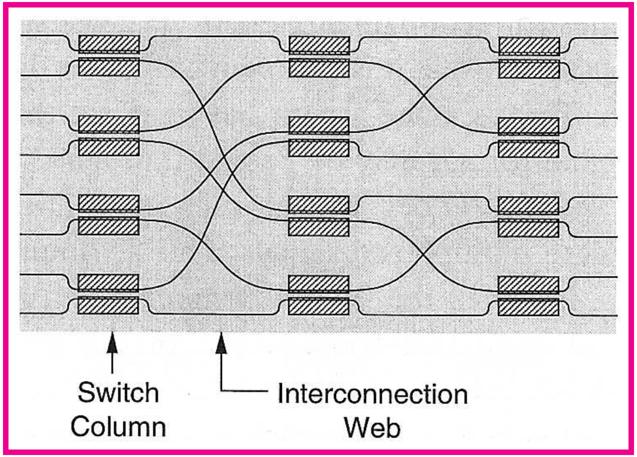
- Simplest switch: a Y junction with one input and two output ports.
- Normally, Y junctions simply split input into two parts.
- If a mechanism is incorporated that allows input signal to exit from a specific port in a controlled fashion, a Y junction is converted into an optical switch.
- Simple solution: Insert a semiconductor optical amplifier (SOA) in the two output branches of a Y junction.
- SOA acts as an absorber without electrical current, but amplifies the signal when current is injected into it.
- Switches that work through selective absorption or amplification of input are referred to as gate switches.

Electro-Optic Switches



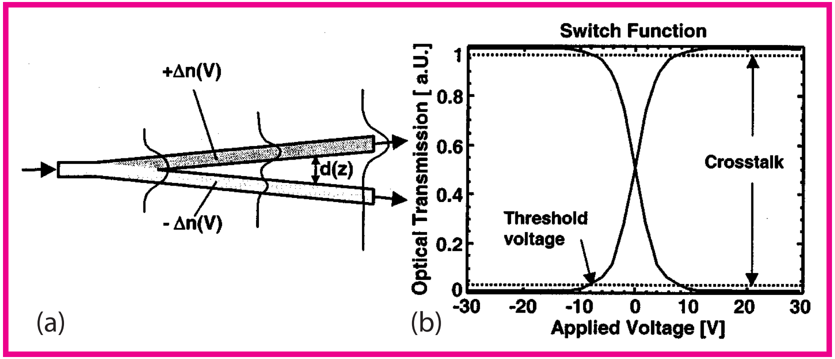
- Make use of electro-optic effect (electro-refraction).
- Provide relatively fast switching on a time scale of ∼1 ns.
- Can be made using Y junctions, directional couplers, or Mach–Zehnder interferometers.
- $LiNbO_3$ technology often used in practice to realize polarization-independent switching.

Directional-coupler Switch



- An 8×8 switching module designed with 12 interconnected directional couplers.
- By 1995, such switching exhibited low crosstalk and excellent uniformity among all connecting ports.
- Such devices have been used for test-bed demonstrations.

Y-Junction Digital Switch



- Switching characteristics of a Y-junction electro-optic switch.
- Referred to as a digital switch because of its binary response.
- External voltage applied to change mode index.
- When opposite voltages are applied to two waveguides, index changes direct the output toward a selected port.
- Voltage-induced asymmetry converts a Y junction into a digital optical switch.

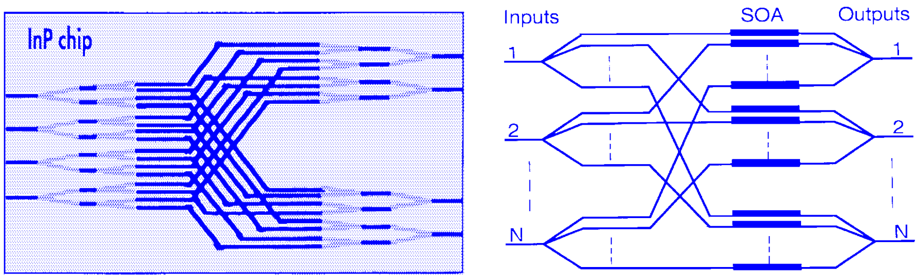
Theory Behind Digital Switch

- Coupling between two waveguides decreases exponentially as they separate from each other.
- Since spacing between waveguides increases linearly with z, coupling coefficient has the form $\kappa = \kappa_0 \exp(-\gamma z)$.
- γ is proportional to the branching angle θ.
- Coupled-mode theory predicts that power changes with V as

$$P_1(V) = \frac{P_{\text{in}} e^{-aV}}{1 + e^{-aV}}.$$

- Constant a depends on θ and other design parameters.
- Power drops to nearly zero as V is increased above a threshold value V_{th} (typically V_{th} <10 V).

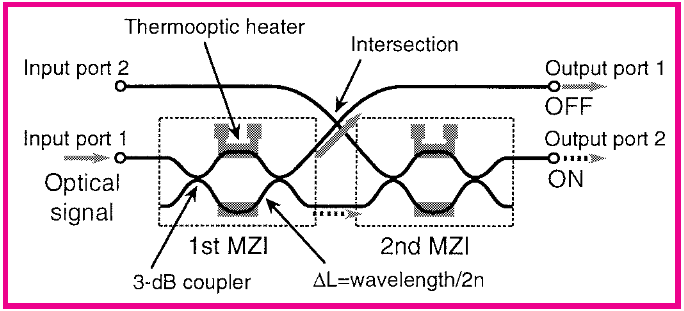
Semiconductor-Waveguide Switches



(a) (b)

- Examples of optical switches based on semiconductor waveguides.
- GaAs or InP waveguides used in combination with SOAs. In (a) SOAs compensate insertion losses; In (b) SOAs act as a gate switch.
- One can employ direction couplers, MZ interferometers, or Y junctions as building blocks.
- InP technology used commonly near 1.55 μm.
- All components can be integrated on the same InP substrate.

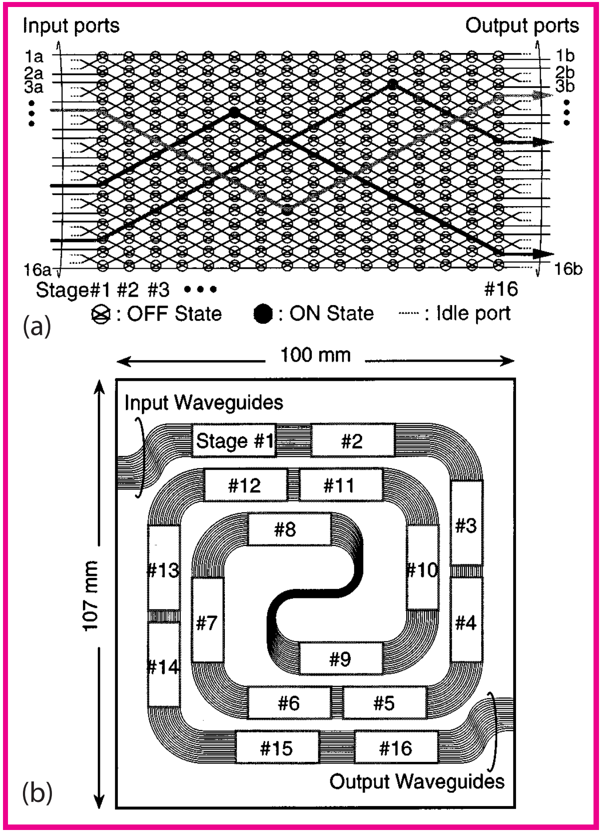
Thermo-Optic Switches



- Make use of MZ configurations and silica-on-silicon technology.
- Refractive index changed in one MZ arm thermally with a thin film of chromium deposited on top of silica waveguide.
- Before heating, input signal comes out of cross port; it is switched to bar port thermally.
- A thermo-optic switch with high extinction ratio is made by combining two MZ interferometers.
- Switching time is $\sim$1 ms for such devices.

Thermo-Optic Switches

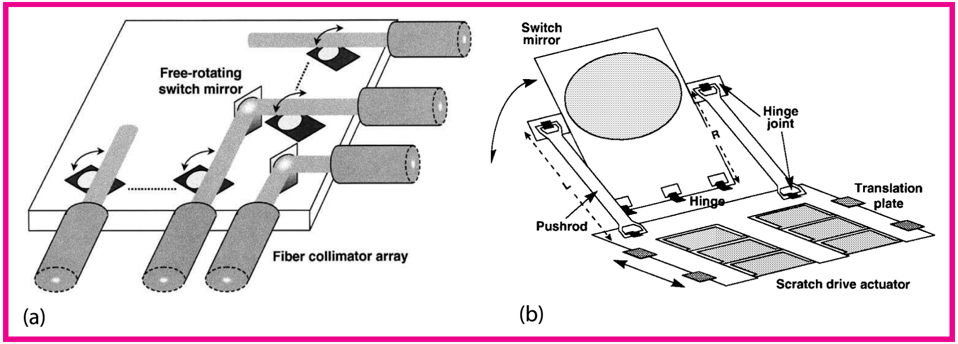
- Circuit layout of a 16×16 switching fabric.
- Uses 256 thermo-optic switches, each containing two MZ interferometers.
- Built in 16 stages.
- Average insertion loss about 6.6 dB.
- Average extinction ratio about 63 dB.



Micro-Mechanical Switches

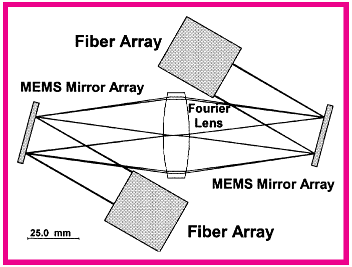
- A mirror acts as a switch if the direction of signal can be changed by tilting the mirror.
- Use of "bulk" mirrors is impractical as a large number of switches are needed for making even 16×16 switching fabric.
- Micro-electro-mechanical system (MEMS) technology is employed in practice.
- It can be used to fabricate microscopic mirrors (micromirrors) that can be rotated by applying an electric signal.
- MEMS devices operate in 2-D and 3-D configurations depending on how mirrors are rotated.

2-D MEMS Switches



- 2-D MEMS switch and details of micromirror design.
- Entire matrix of micromirrors can be integrated monolithically on a single silicon chip.
- Input from one fiber can be forced to couple into any output fiber by flipping the micromirror lying at intersection.
- For 1-mm spacing between micromirrors, chip size is 2×2 cm^2 for a 16×16 switch.

3-D MEMS Switches

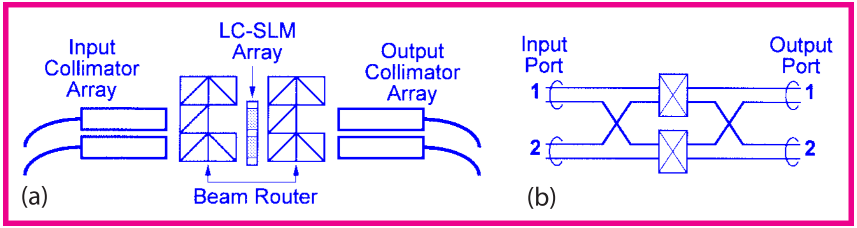


- 2-D geometry requires N^2 micromirrors for $N \times N$ MEMS switch.
- 3-D configuration requires two arrays of N micromirrors.
- Each micromirror is a two-axis gimbal mirror and it steer input beam in any direction.
- Angle of mirror can be adjusted electronically to make interconnections.
- Fourier lens helps to reduce the crosstalk.
- 3-D MEMS switches with $N = 1100$ made by 2003.

Liquid-Crystal Switches

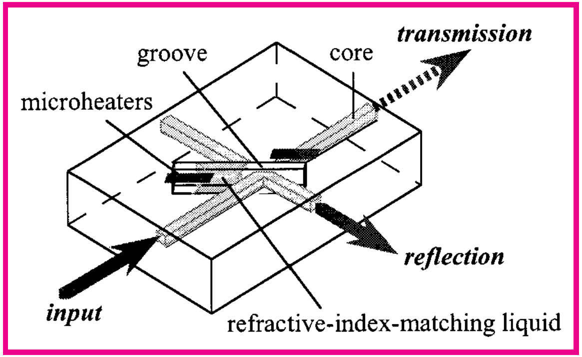
- Liquid crystals are used for making computer displays and spatial light modulators.
- When a thin layer of nematic liquid crystal is surrounded by polarizers, incident light can be transmitted or blocked, depending on an external voltage.
- Physical process: electrically controlled birefringence.
- State of polarization of incident light changes with applied voltage.
- Device is designed such that no light passes through in the absence of applied voltage (OFF state).
- With a suitable voltage, birefringence is changed such that incident light passes through (ON state).

Design of Liquid-Crystal Switches



- Polarization-sensitivity problem is solved by splitting input signal into orthogonally polarized components.
- Polarization beam splitters are used in combination with beam routers.
- If both switches are in OFF state, signal entering from port 1 is routed to output port 2.
- When both switches are in ON state, input from port 1 appears at output port 1.
- A 32×32 switch was made as early as 1998.

Bubble Switches



- Bubble technology makes use of total internal reflection.
- Two planar waveguides intersect in a groove filled with a liquid whose refractive index nearly matches that of waveguide mode.
- When a thermally generated bubble is at the intersection, reflected beam is coupled into the other waveguide.
- Switching accomplished using microheaters (switching time close to 10 ms).

Design of Bubble Switches

- To fabricate a bubble-based switch, a two-dimensional array of waveguides is formed such that they intersect inside liquid-filled channels.
- Waveguide array is made in the form of a planar lightwave circuit with silica-on-silicon technology.
- Liquid-filled channels are etched chemically (typically 15-μm-wide).
- Air bubble is generated with the inkjet technology used for printers.
- A 32×32 switch was made by 2000 with bubble technology.
- A bubble switch is similar to MEMS switch in the sense that both employ reflection for switching.
- MEMS use real mirrors, while total internal reflection is employed for a bubble switch.

Wavelength-Domain Routers

- Switch individual channels to different ports in a passive manner.
- Switching performed by a built-in grating on the basis of channel wavelengths.
- A WDM router is also called a static router since routing topology is not dynamically reconfigurable.
- Each WDM signal is demultiplexed and directed toward different output ports of the router.
- Channels are distributed in a cyclic form.
- In a common design, an arrayed waveguide grating is employed.

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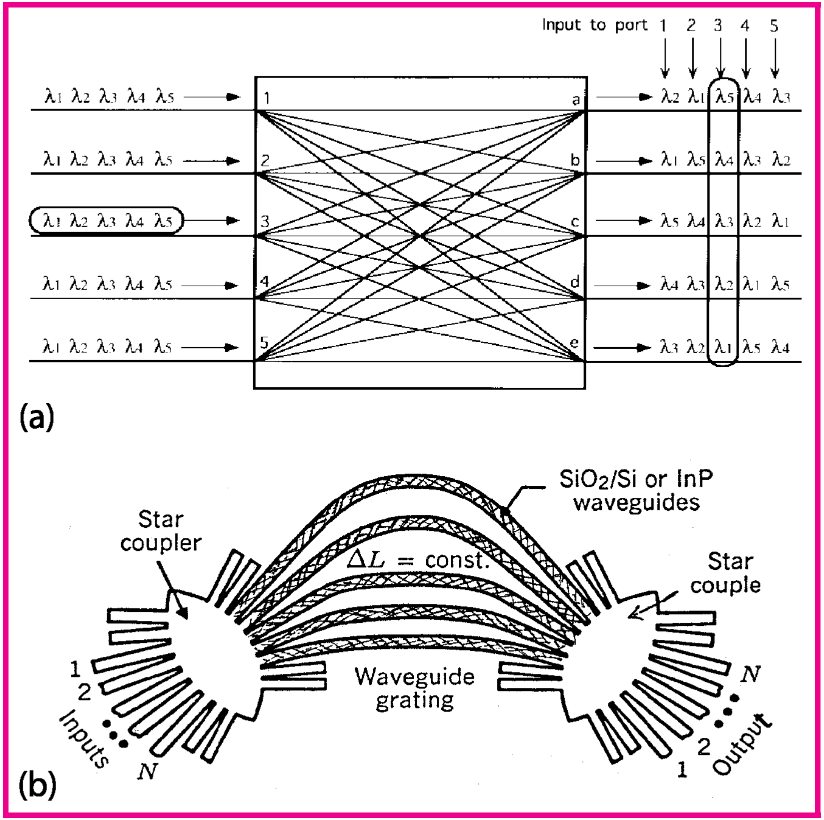
Waveguide-Grating Routers



Back

Close

Waveguide-Grating Routers

- A waveguide-grating router (WGR) consists of an arrayed waveguide grating between two star couplers.
- A single input is divided into M parts, which acquire different phase shifts and interfere at the second star coupler (a kind of multi-arm MZ interferometer).
- Phase difference for a signal traveling from pth input port to qth output port through the mth waveguide can be written as

$$\phi_{pqm} = (2\pi m/\lambda)(n_1\delta_p + n_2\Delta L + n_1\delta'_q).$$

- n_2 = mode index in waveguide; n_1 = index of star couplers; δ_p and δ'_q depend on the location of input and output ports.
- When $n_1(\delta_p + \delta'_q) + n_2\Delta L = Q\lambda$, all fields coming out of the M waveguide interfere constructively at the qth port.

Physics Behind WGR

- Multiple wavelengths entering from the pth port are directed to different output ports.
- Phase condition can be satisfied for many integer values of Q.
- If Q is changed to $Q+1$, a different wavelength is directed toward the same port.
- Frequency difference between these two wavelengths corresponds to free spectral range of the router:

$$\mathrm{FSR} = \frac{c}{n_1(\delta_p + \delta_q') + n_2 \Delta L}.$$

- If δ_p and δ_q' are small compared with ΔL, FSR becomes nearly constant for all ports.

Design of WGRs

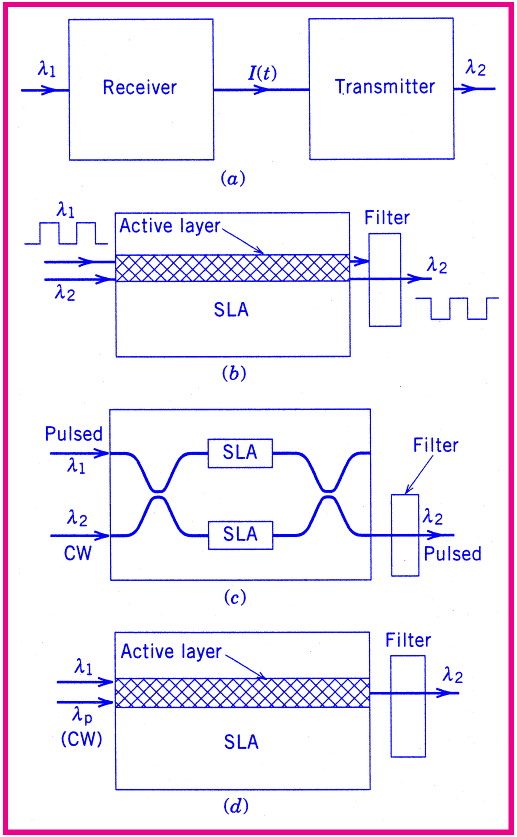
- Optimization of a WGR requires precise control of many design parameters.
- Main design goals: low crosstalk and high routing efficiency.
- Despite complexity of design, WGRs are routinely fabricated in the form of a compact commercial device (size ∼1 cm).
- Silica-on-silicon technology is used in practice.
- WGRs with 128 input and output ports were available by 1996 in the form of a planar lightwave circuit.
- Such devices can work with a channel spacing as small as 0.2 nm while maintaining crosstalk below 20 dB and insertion losses around 6 dB for all channels.

Wavelength Converters

- Optical networks not transparent in the wavelength domain.
- Channel blocking occurs if two channels at the same wavelength are destined for the same location.
- This problem can be solved using wavelength converters.
- A wavelength converter transfers the channel to a new wavelength without modifying its data content.
- Many schemes were developed during 1990s for realizing wavelength converters.
- A simple scheme employs a receiver-transmitter pair.
- Its main disadvantage is conversion to electric domain.
- All-optical wavelength converters are preferred in practice.

Schemes for Wavelength Conversion

- Optoelectronic regeneration (receiver–transmitter pair).
- Cross-gain saturation in a semiconductor laser amplifier (SOA).
- Cross-phase modulation in SOA using a MZ interferometer.
- Four-wave mixing inside a SOA.



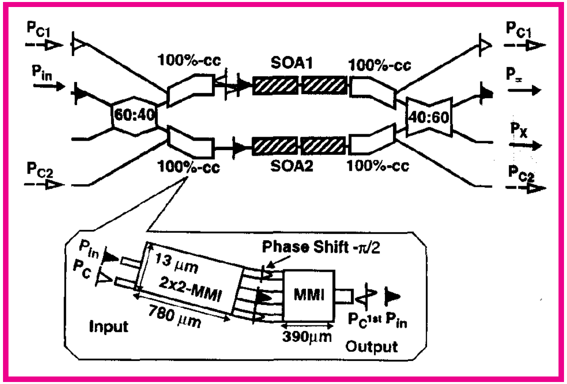
Cross-Gain Saturation in SOAs

- Signal at λ_1 is launched into SOA together with low-power CW beam at λ_2 (desired wavelength).
- During 0 bits, CW beam amplified considerably (no saturation.
- CW beam is amplified by a much smaller amount during 1 bits.
- Bit pattern is transferred to the λ_2 with reverse polarity (1 and 0 bits are interchanged).
- This technique can work at bit rates as high as 40 Gb/s.
- Its main disadvantages are relatively low on–off contrast, degradation due to spontaneous emission, and phase distortion because of frequency chirping.
- The use of an absorbing medium in place of the SOA solves polarity reversal problem.

Cross-Phase Modulation in SOAs

- Contrast problem can be solved using Cross-phase modulation.
- An SOA is inserted in one arm of a MZ interferometer.
- In the absence of λ_1 beam, MZ is balanced, and CW beam at λ_2 exits from the cross port.
- Signal at λ_1 injected such that its power passes through the arm containing SOA.
- It modifies the phase of λ_2 beam by π only during 1 bits and directs then toward the bar port.
- An optical filter blocks the original λ_1 signal.
- Other types of interferometers can also be used.

XPM-Based Wavelength Converters



- Two SOAs and several MMI couplers are monolithically integrated on a single InP chip in the MZ configuration.
- Two control signals P_{c1} and P_{c2} are coupled into two MZ arms using an especially designed MMI coupler.
- This coupler converts control signals into first-order modes, while signal remains in the fundamental mode.
- Control signals converted back into fundamental mode for re-use.

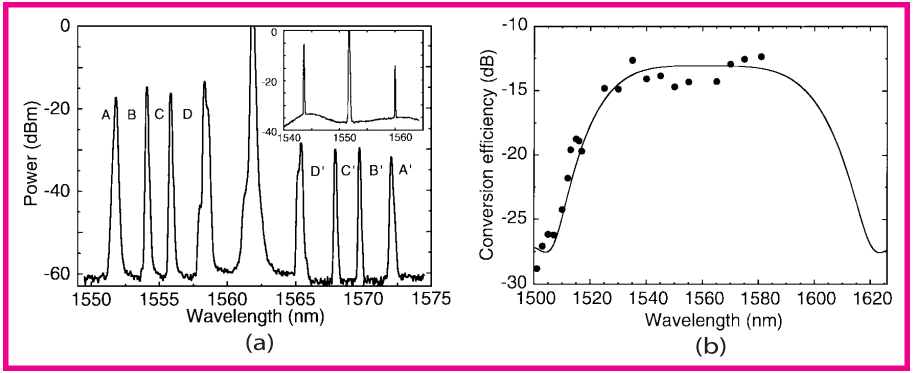
Four-Wave Mixing in SOAs

- Another scheme employs SOA as a nonlinear medium for FWM.
- FWM requires an intense CW pump beam that is launched into SOA together with the signal channel.
- If ν_1 and ν_2 are frequencies of input and converted signal, pump frequency $\nu_p = (\nu_1 + \nu_2)/2$.
- At the SOA output, a replica of the input signal appears at ν_2.
- A filter blocks the original channel at ν_1.
- This technique works at bit rates of up to 100 Gb/s.
- Its main disadvantage is that it requires a tunable high-power laser acting as a pump.

$LiNbO_3$-Based Wavelength Converter

- Wavelength converters can also be made with $LiNbO_3$ technology.
- $\chi^{(2)}$ is used for difference-frequency generation.
- Periodic poling used for realizing quasi-phase matching; sign of $\chi^{(2)}$ inverted periodically along waveguide length.
- Such devices require a pump laser operating near 780 nm with 50–100 mW of power.
- An alternative scheme makes use of two cascaded second-order nonlinear processes in a PPLN waveguide.
- It works with a pump laser operating near 1.55 μm.
- Pump at ω_p is first up-converted to $2\omega_p$, which then generates wavelength-shifted output through difference-frequency generation.

$LiNbO_3$-Based Wavelength Converters

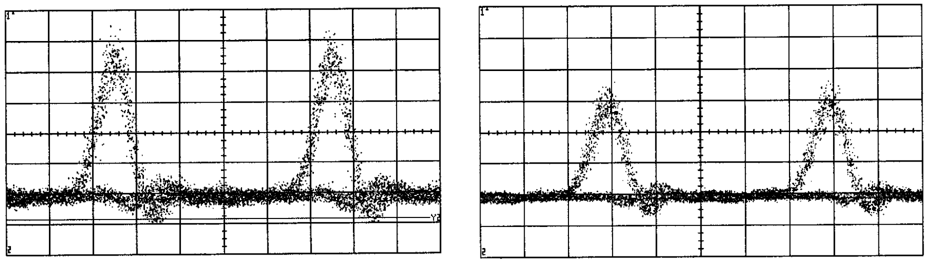


- Simultaneous wavelength conversion of four channels in a PPLN waveguide pumped at 1562 nm with 110-mW power.
- Conversion efficiency about 5% for all channels.
- Bandwidth of flat region over which conversion efficiency is nearly constant is more than 60 nm.
- Wavelength conversion at 160 Gb/s demonstrated in 2000.

Fiber-Based Wavelength Converters

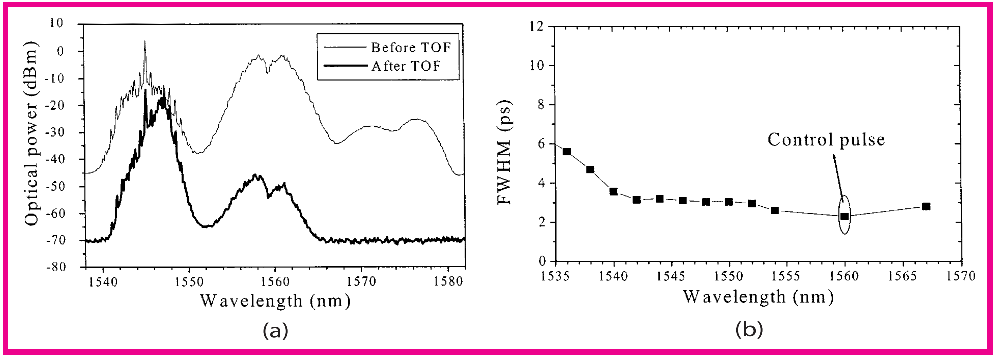
- Both XPM and FWM inside fibers can be used for wavelength conversion.
- In the XPM case, signal is launched with a CW seed at the desired wavelength.
- Signal imposes XPM-induced phase shift during time slots of 1 bits.
- This phase shift is converted into amplitude modulation a MZ or Sagnac interferometer.
- By 2000, a nonlinear optical loop mirror provided wavelength converters capable of operating at 40 Gb/s.
- Device reflected all 0 bits but 1 bits were transmitted because of XPM-induced phase shift.

Fiber-Based Wavelength Converters


(a) (b)

- On–off ratio of the converted signal should be large.
- It was measured to be 25 dB in an experiment employing 3-km-long Sagnac loop.
- Optical eye diagrams for the original and wavelength-converted signals show little degradation.
- It is not essential to use an optical interferometer.
- One can pass phase-modulated output through an optical filter.

XPM-Based Wavelength Converters

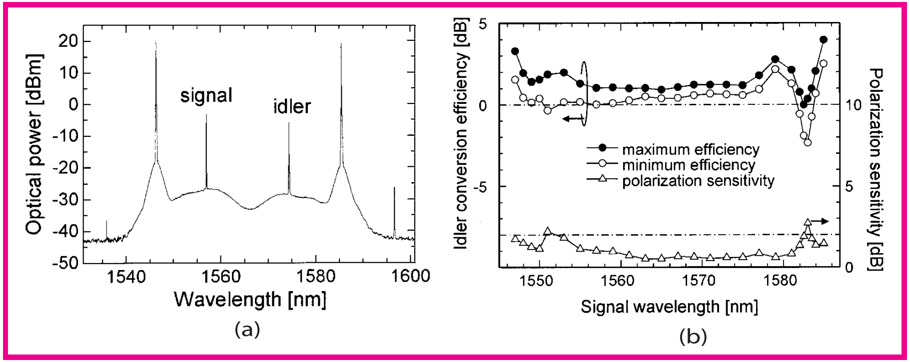


- XPM creates sidebands on each side of carrier (FM sidebands).
- Optical filter blocks the carrier but lets one of the sidebands pass.
- Filtered output is a replica of the original bit stream at a shifted wavelength.
- Wavelength of a 80-Gb/s signal could be shifted by several nanometers with this technique.
- Fiber length was reduced to 1 km using a narrow-core fiber.

FWM-Based Wavelength Converters

- Use of FWM for wavelength conversion requires fiber-optic parametric amplifiers.
- Such amplifiers need one or two high-power pump lasers.
- SBS problem is solved by modulating phase of each pump at high frequencies (>1 GHz).
- Such phase modulation can lead to considerable spectral broadening of wavelength-converted signal.
- Idler field is generated such that $A_i \propto A_{p1} A_{p2} A_s^*$.
- If pump phases are modulated in reverse ($\phi_2 = -\phi_1$), the product $A_{p1} A_{p2}$ does not exhibit any phase modulation.
- Idler spectrum is then a mirror image of signal spectrum.

FWM-Based Wavelength Converters

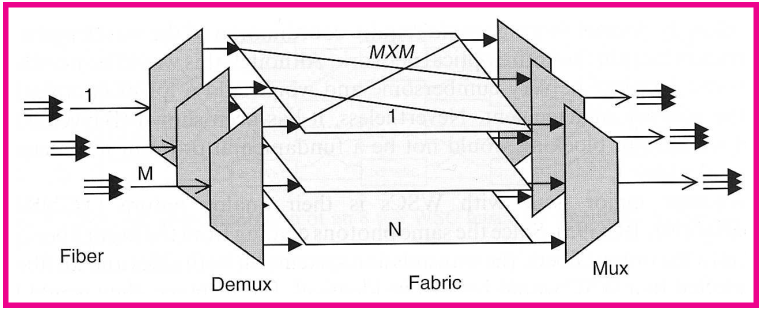


- Two dominant peaks correspond to two orthogonally polarized pumps at 1585 and 1546 nm with 118 and 148 mW powers, respectively.
- Power was higher at the shorter wavelength to offset Raman-induced power transfer.
- FWM occurred in a 1-km-long highly nonlinear fiber ($\gamma = 18\ \mathrm{W}^{-1}/\mathrm{km}$).
- Idler power was comparable to that of the signal, indicating nearly 100% efficiency for the wavelength converter.

Optical Cross-Connects

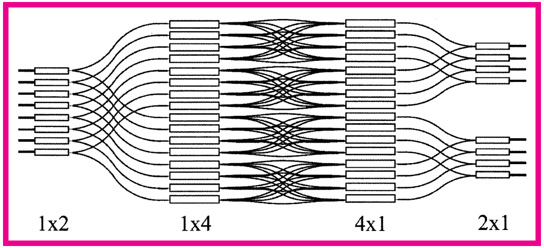
- OXCs perform the function of electronic cross-connects but keep the WDM signals in the optical domain.
- They make use of optical switches in place of electronic switches.
- Use of WDM technology makes the design of OXCs complex.
- Individual channels must be demultiplexed before any switching can occur.
- OXCs can be divided into two groups:
  - Wavelength-Selective Cross-Connect
  - Wavelength-Interchanging Cross-Connect
- Many OXC designs have been developed for future all-optical networks.

Wavelength-Selective Cross-Connects



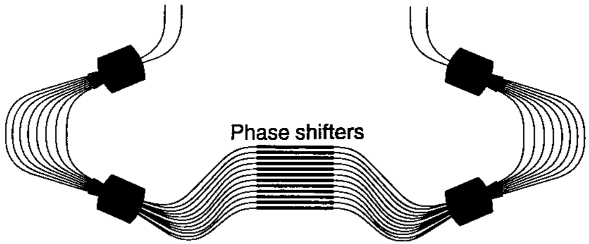
- Individual wavelengths sent to a separate switching unit.
- An OXC with N input and M output ports needs N switching units if each port receives N WDM channels.
- Such an OXC needs M multiplexers, M demultiplexers, and N switching units with M input and M output ports.
- Such devices are relatively easy to fabricate using silica or InP waveguides.
- Required switching time for OXCs is 5 ms or less.

Coupler-Based Cross-Connects



- Schematic of 8×8 switching unit designed using MMI couplers.
- Device fabricated with silica-on-silicon technology.
- Employs 8 1×2 couplers, followed by 16 1×4 MMI couplers.
- On the output side, signals are recombined using sixteen 4×1 and eight 2×1 MMI couplers.
- Switching performed by multiple MZ interferometers.
- Total insertion loss <6 dB and crosstalk level< −34 dB.

AWG-Based Cross-Connects



- Schematic of an InP-based OXC in which switching is performed using phase shifters placed in between two AWGs.

- By controlling the amount of phase shift, it is possible to connect any input channel to any output channel.

- InP devices are sensitive to the state of polarization of input signal.

- Polarization-independent OXC were built as early as 1998 using electro-optic MZ switches.

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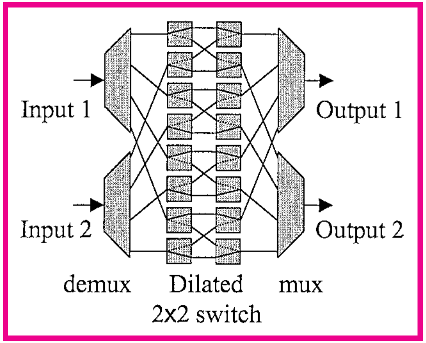
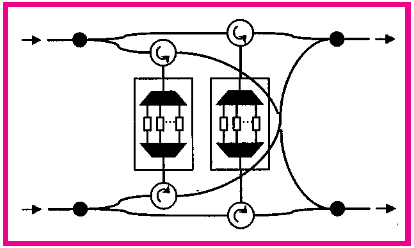
MZ-Based Cross-Connects



- Crosstalk is a major issue for all OXCs.
- Crosstalk can be reduced using double-gate switches.
- Each wavelength from input fibers is handled by a switch composed of four MZ interferometers.
- Phase shifts in MZ arms induced with the electro-optic effect.
- High insertion losses prevent InP devices from being competitive with OXCs based on silica waveguides.

Circulator-Based Cross-Connects

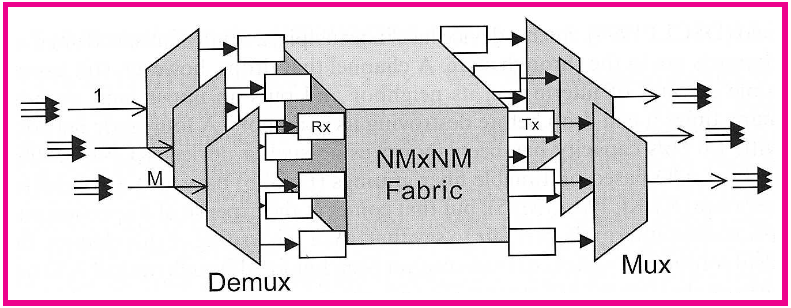


- Each WDM signal entering is first split into two parts by a 3-dB coupler.
- Each part is sent to a wavelength blocker surrounded by two optical circulators.
- Left blocker controls bar state; right one controls cross state.
- If a WDM channel needs to be maintained in the bar state, it is passed by the left blocker but blocked by the right one.
- Wavelength blockers work though phase shifts introduced in one arm of MZ switches.

Merits of Wavelength-Selective OXCs

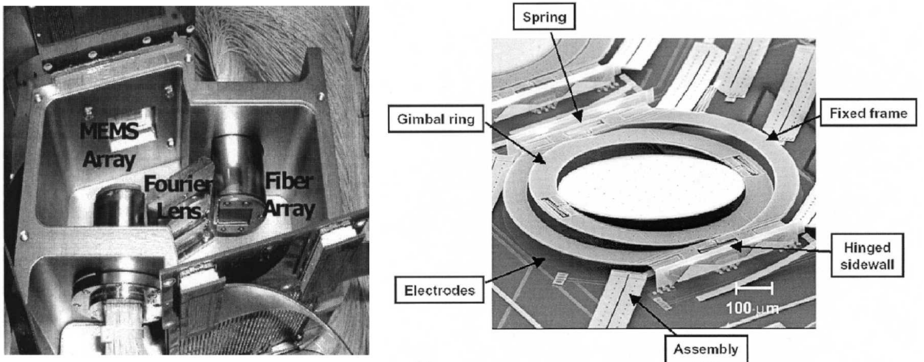
- Main advantage: all-optical design.
- Such OXCs do not require opto-electronic regenerators.
- They are transparent to the format and bit rate of WDM channels.
- These advantages are overshadowed by wavelength-blocking nature of wavelength-selective OXCs.
- Blocking occurs when two channels entering from different input ports at the same wavelength are destined for the same output port.
- Blocking problem can be solved with a proper assignment of transmitter wavelength.
- Coordination of wavelengths throughout the entire is not an easy task in practice.

Wavelength-Interchanging Cross-Connects



- Solve wavelength-blocking problem using wavelength converters.
- In contrast with a wavelength-selective OXC, channels at a given wavelength are not grouped together.
- Require a larger $NM \times NM$ switch to interconnect NM channels.
- This switch can even be electrical; receivers convert all channels into electrical domain at the input end, while optical transmitters are used to regenerate channels.

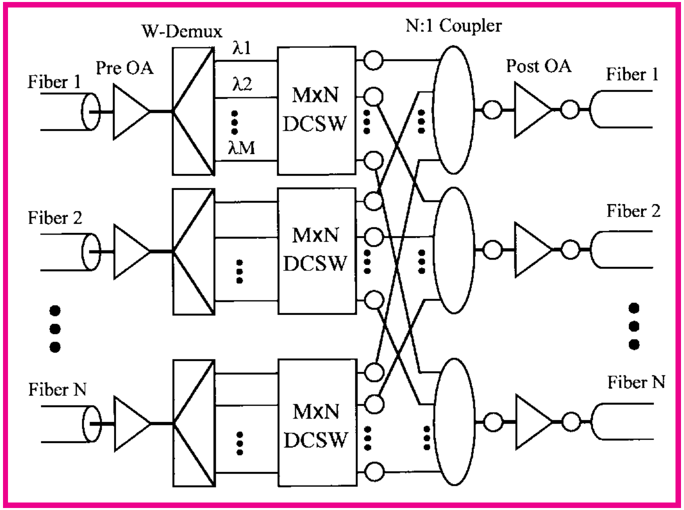
MEMS-Based Cross-Connects



(a) (b)

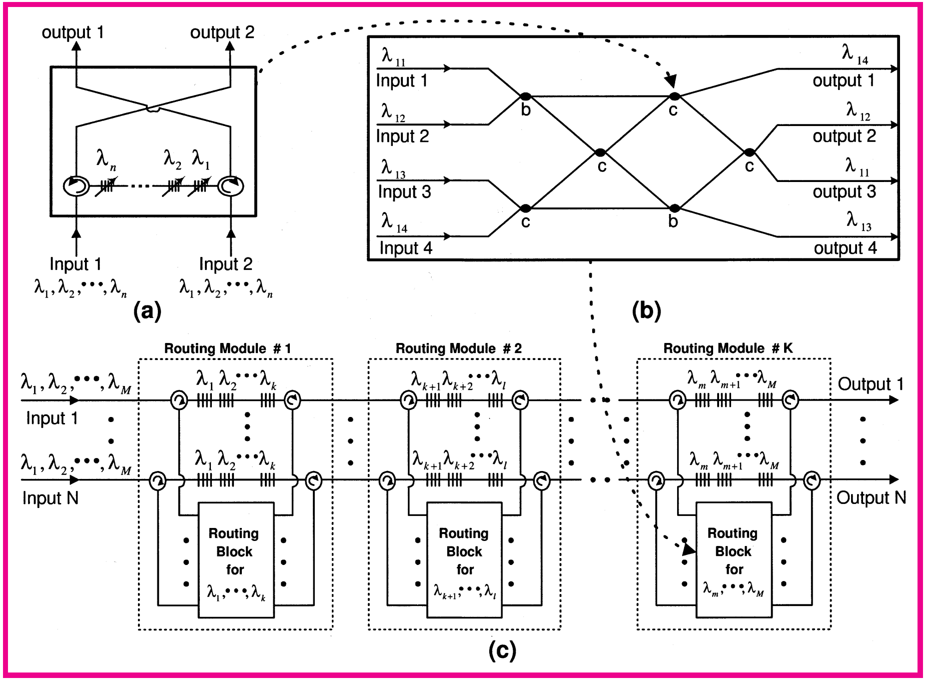
- Any switching technology can be employed for making OXCs.
- Use of 3-D MEMS switches has attracted most attention.
- Such OXCs employ micromirrors that rotate to make interconnection among input and output fibers.
- By 2003, such OXcs could interconnect more than 1000 input and output ports.

DCSW-Based Cross-Connects



- OXC architecture based on delivery and coupling switches (DCSW).
- It makes use of N switches with M input and N output ports.
- Such switches are made with silica-on-silicon technology.
- Insertion losses fall in the range of 12–14 dB.

Fiber-Grating-Based Cross-Connects



Tunable fiber Bragg gratings used in combination with optical circulators to make 2×2 switching units; six of them combined to make a routing block, which in turn used to form the OXC.

Fiber-Grating-Based Cross-Connects

- FBGs reflect or transmit a channel depending on whetner channel wavelength falls within the stop band or outside of it.
- In a 2×2 switching unit, FBGs are tuned such that each channel can be switched to either output port.
- Six such 2×2 switches can be combined to produce a 4×4 routing block.
- Several such routing blocks are then combined to design the entire OXC.
- This architecture does not require demultiplexing and subsequent multiplexing of the WDM signals.
- Its modular nature permits upgrading the number of wavelengths as needed.

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Time-Domain Switching

- In the case of space-domain switching, entire WDM channel is switched to another port without affecting its information content.
- In time-domain switching, individual bits, or packets of bits, belonging to a specific channel are switched to different ports.
- Main difference between two kinds of switching is switching speed.
- Whole-channel switching to a different port is acceptable on a time scale $\sim$1 ms.
- Time-domain switching must occur on the time scale of individual bits or packets (1 ns or shorter).
- In the case of time-division multiplexing, such switches must operate on a time scale $<$10 ps when bit rate is 100 Gb/s.

Nonlinear Switching Schemes

- Time-domain switching requires an optical switch capable of responding at a time scale ∼1 ps.
- Such switches are referred to as an optical gate that can be opened for a short time using an external control.
- Nonlinear effects such as optical bistability, XPM, and FWM are exploited for time-domain switching.
- Switching speed depends on the nonlinear medium employed.
- Optical fibers allow ultrafast switching (time scale $<$0.1 ps), but require high optical powers and long fiber lengths.
- Semiconductor optical amplifiers (SOAs) exhibit stronger nonlinearities but respond on a nanosecond time scale.

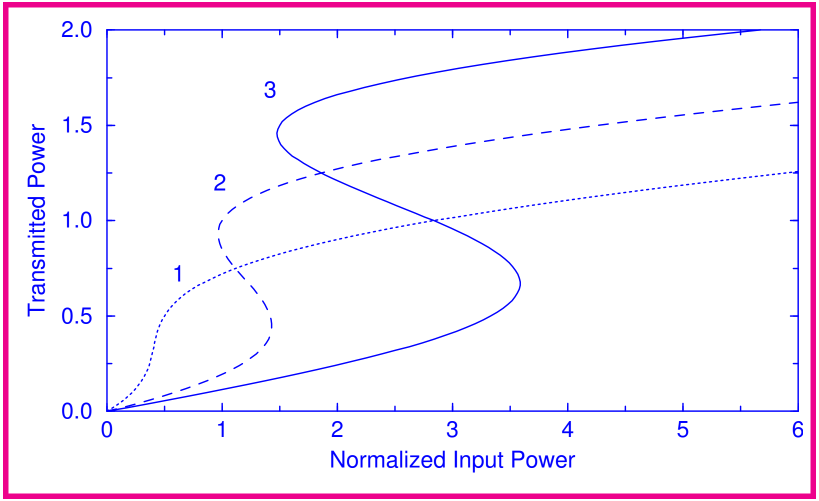
Optical Bistability

- Under certain conditions, output can have two discrete stable values for the same input.
- If output can be switched between these two values through an external time-dependent control, device acts as a time-domain switch.
- A Fabry–Perot or a ring resonator containing a nonlinear medium $(n = n_l + n_2 I)$ exhibits bistability.
- For high-finesse resonators, transmitted power satisfies

$$P_t \left\{ 1 + \frac{4R_m}{(1-R_m)^2} \sin^2 \left[\frac{\phi_0}{2} + \frac{\gamma P_t L_R}{2(1-R_m)} \right] \right\} = P_i.$$

- Multiple values of P_t are possible for the same incident power P_i because of nonlinear phase shift $\gamma P L_R$.

Bistable Response



- Bistable response of a fiber resonator with $R_m = 0.5$ for three values of detuning $\delta = (\omega - \omega_0)\tau_r$.
- Cavity Round-trip time $\tau_r = L_R/v_g$.
- S-shaped curve is a signature of optical bistability.

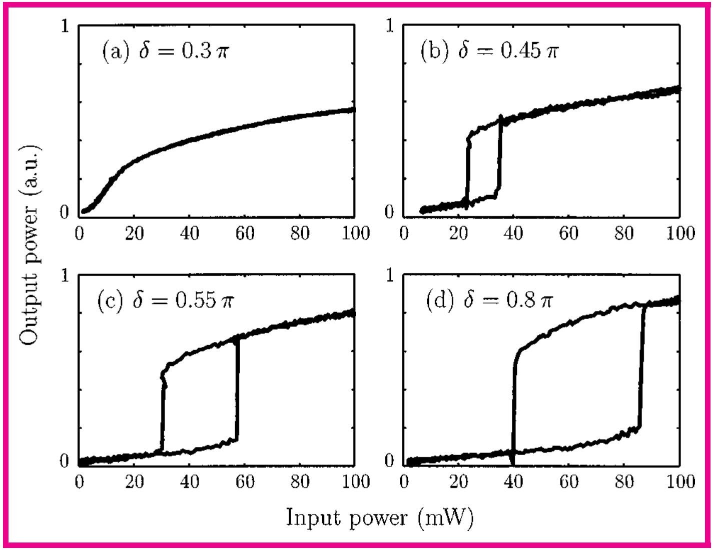
Physics Behind Bistable Response

- Low output when linear phase shift ϕ_0 does not correspond to a FP resonance ("off" state).
- Nonlinear phase shift affects the cavity resonances.
- Ar a critical power level, it brings the signal onto a resonance, resulting in higher transmission ("on" state).
- Over a certain range of δ, three solutions produce the S-shaped curve associated with optical bistability.
- Middle branch with a negative slope is always unstable.
- Transmitted power jumps up and down at specific values of P_i in such a way that it exhibits hysteresis.
- Hysteresis allows the device to act as an optical switch.

Materials for Optical Bistability

- A Bistable device can be switched on and off by changing input power, input wavelength, or other controls that change detuning δ.
- Optical bistability has been observed in atomic vapors, semiconductor waveguides, and optical fibers.
- As early as 1978, a $LiNbO_3$ waveguide modulator was used for this purpose by coating its two ends with silver to form an FP cavity.
- Waveguides formed using multiple quantum wells were used during the 1980s to observe bistability.
- In the case of optical fibers, SBS hampers the observation of optical bistability when CW beams are used.
- Bistability in a fiber-ring resonator was first seen in a 1983 experiment in which SBS was avoided using picosecond pulses.

Experimental Results

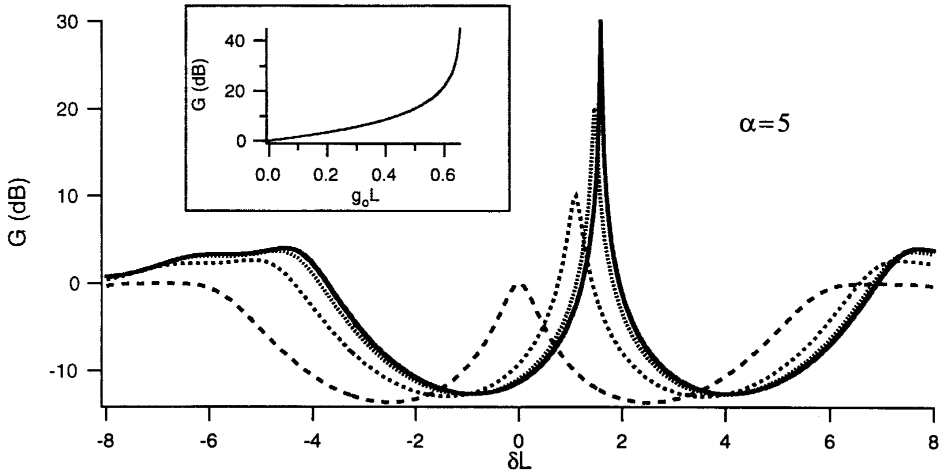


- A 1998 experiment employed fiber-ring resonator (length 7.4 m).
- Mode-locked pulses (width ∼1 ps) from a Ti:sapphire laser were used to observe bistability.
- Figure shows Hysteresis cycle four values of detuning δ.

Bistability with Distributed Feedback

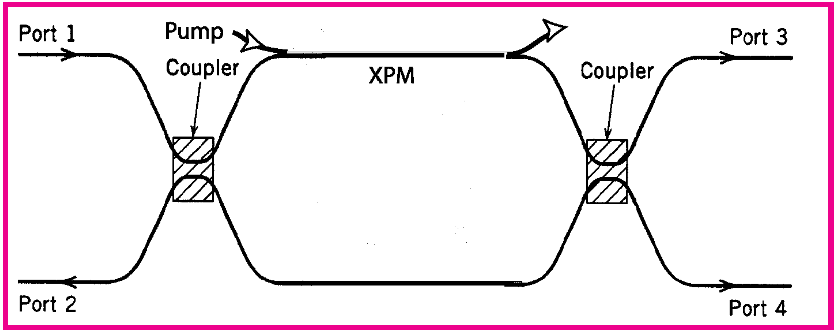
- FP cavity is not essential for bistability as long as there is a built-in mechanism for optical feedback.
- DFB from a Bragg grating formed inside a nonlinear medium can lead to optical bistability.
- DFB semiconductor lasers and amplifiers are a natural candidate for such devices.
- Physical mechanism: Dependence of refractive index on carrier density.
- As carrier density decreases in response to gain saturation, refractive index increases, leading to a shift of stop band.
- This nonlinear shift of the stop band brings the device into resonance to produce bistability.

Bistability in DFB Amplifiers



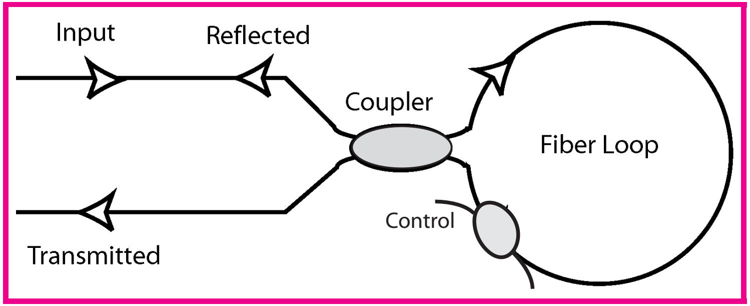
- Gain as a function of detuning (from Bragg wavelength) in a DFB amplifier (a laser biased below threshold).
- Stop band shifts as more current is injected because of a change in carrier density.
- Four curves correspond to a peak gain of 0, 10, 20, and 30 dB.

Cross-Phase Modulation



- XPM can be used for switching without requiring a resonator.
- Its use requires a Mach–Zehnder (or Sagnac) interferometer for converting XPM-induced phase shift into amplitude changes.
- Signal is directed toward cross port in the absence of control.
- A control pulse is used in one MZ arm to induce a π phase shift.
- A temporal slice of input signal then appears at the bar port.
- Minimum duration of temporal slice <1 ps in optical fibers.

Switching with Sagnac Loops



- It is hard to maintain identical path lengths in two MZ arms ($>$1 km because of weak nonlinearity of silica fibers).
- A Sagnac loop solves the stability problem.
- To make a time-domain switch, control signal is injected in only one direction to produce a π phase shift.
- Only a temporal slice of input overlapping with control is reflected.
- Each slice can be quite short because of fast fiber response.

Walk-Off Effects

- Even though fiber responds at femtosecond time scales, several other factors limit switching speed to >1 ps.
- Wavelengths of the control and signal pulses are different in practice.
- Because of dispersion, two pulses travel at different speeds.
- Even if pulses overlap initially, they walk away from each other after some distance (walk-off effect).
- Such a walk off reduces the effectiveness of XPM.
- Phase difference $\Delta\phi$ between counterpropagating fields is given by

$$\Delta\phi(t) = \phi_a^{\mathrm{NL}} - \phi_b^{\mathrm{NL}} = 2\gamma \int_0^L [P_c(t - \delta z) - P_c(t - \delta' z)]\, dz.$$

- Group-velocity mismatch: $\delta = \frac{1}{v_s} - \frac{1}{v_c}, \quad \delta' = \frac{1}{v_s} + \frac{1}{v_c}.$

Back
Close

Transmissivity of Sagnac Loop

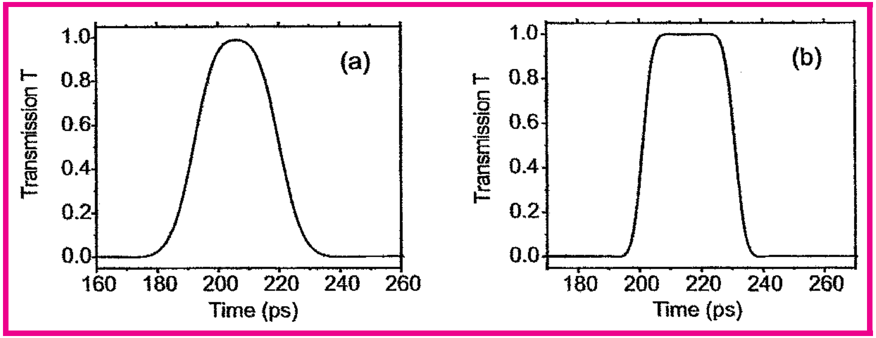
- For a Gaussian control pulse, $P_c(t) = P_0 \exp(-t^2/T_0^2)$.
- Integrals can be performed analytically in this case.
- In the counterpropagating direction, relative speed is so large that XPM-induced phase shift is negligible, and

$$\Delta\phi(t) = \frac{\gamma L E_c}{T_W}\left[\mathrm{erf}\left(\frac{T_W - t}{T_0}\right) - \mathrm{erf}\left(\frac{-t}{T_0}\right)\right].$$

- $E_c = \sqrt{\pi} P_0 T_0$ is control-pulse energy and $T_W = \delta L$ is the total walk off in a loop of length L.
- Loop transmissivity is given by $T(t) = 1 - 2\rho(1-\rho)[1 + \cos(\Delta\phi)]$.
- For $\rho = \frac{1}{2}$ (3-dB coupler), $T(t) = \sin^2[\Delta\phi(t)/2]$.

Back
Close

Switching Window

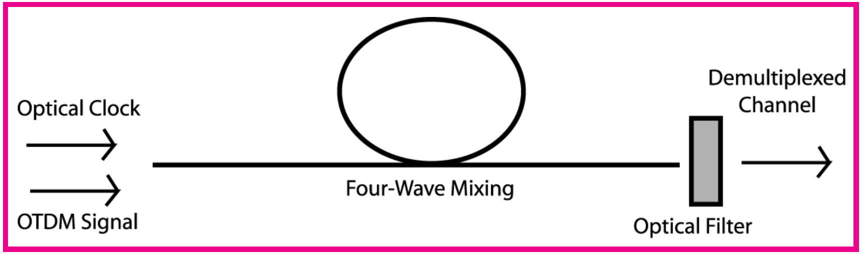


- Switching window of a Sagnac-loop switch for (a) $T_0 = 30$ ps with $T_W = 10$ ps and (b) $T_0 = 10$ ps with $T_W = 30$ ps.
- When $T_W < T_0$, window is governed by control pulse.
- When $T_W > T_0$, window is governed by walk-off effects.
- $T_W = \delta L$ sets the minimum duration of switching window.
- It can be reduced by reducing loop length L or $\delta = \frac{1}{v_s} - \frac{1}{v_c}$.
- Wavelength difference between control and signal should be small.

Reduction of Walk-Off Effects

- Walk off problem can be solved by using a fiber whose zero-dispersion wavelength lies in the middle of control and signal wavelengths.
- It can also be solved using orthogonally polarized control pulses at the same wavelength in a polarization-maintaining fiber.
- Some velocity mismatch may still occur because of PMD.
- It can be avoided by constructing a Sagnac loop in which slow and fast axes are interchanged in a periodic fashion.
- δ then changes from positive to negative periodically.
- Control and signal pulses nearly overlap throughout the fiber, resulting in large XPM-induced phase shift.

Four-Wave Mixing



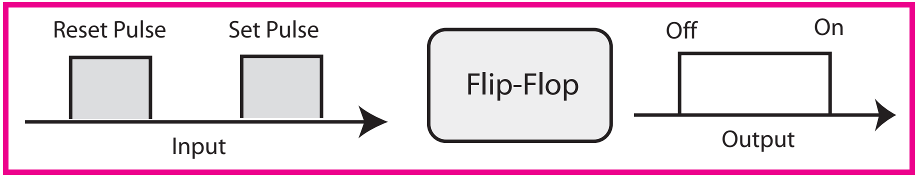
- FWM scheme is similar to that used for wavelength conversion.
- Signal is launched together with the control in the form of a periodic pulse train (an optical clock).
- Clock plays the role of pump for the FWM process.
- In time slots in which clock pulse overlaps with a signal pulse, FWM produces a pulse at the idler wavelength.
- Pulse train at idler wavelength is an exact replica of the channel that needs to be demultiplexed.

Back
Close

Four-Wave Mixing

- FWM in optical fibers first used in 1991 for time-domain switching.
- In later experiments, signal bit rate approached 1 THz, confirming that optical fibers switch pulses shorter than 1 ps.
- FWM-based switches can provide gain while switching signal.
- Fiber length should be 5 km or more for the device to function at practical power levels.
- Required fiber length can be reduced by by using highly nonlinear fibers (small mode size produces large γ).
- Alternatively, a different nonlinear medium (SOA) can be used.
- Switching time limited for SOAs. Several schemes allow use of SOAs at speeds as high as 250 GHz.

Optical Flip-Flops

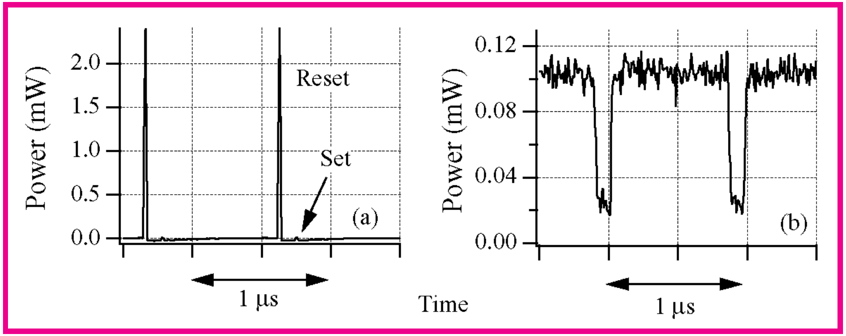


- Functionality similar to electrical flip-flops.
- SOAs often used for making flip-flops (compact size and potential for monolithic integration).
- External control can be electrical or optical.
- Optical control is used in all-optical flip-flops.
- Device switched to on state by sending a set pulse.
- A reset pulse turns the flip-flop off.
- Output remains on between the set and reset pulses. In this sense, a flip-flop acts an optical memory element.

Semiconductor-Based Optical Flip-Flops

- Semiconductor laser or SOAs used for making flip-flops (compact size, low-power consumption, potential for monolithic integration).
- An InGaAsP laser was used in 1987 as an FP amplifier by biasing it slightly below threshold.
- Device could be switched on and off but switching time was relatively long (>1 μs).
- In a 2000 experiment, a DFB laser was biased below threshold.
- Set and reset pulses (15-ns-wide) were obtained from two InGaAsP lasers operating at 1,567 and 1,306 nm.
- Set pulse had a peak power of only 22 μW (0.33-pJ energy).
- Peak power of reset pulses was close to 2.5 mW (36-pJ energy).

DFB-Amplifier Flip-Flops



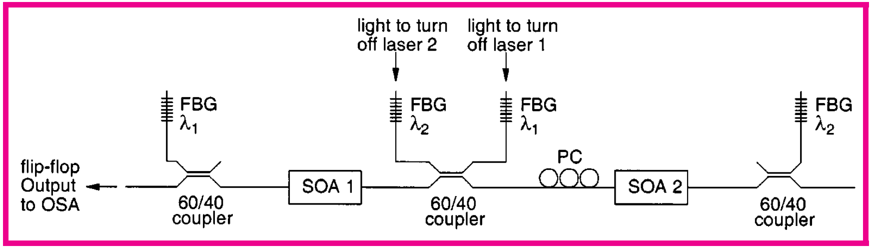
- Characteristics of an optical flip-flop built using a DFB laser biased slightly below threshold.
- Left: Timing sequence of set (small peaks) and reset pulses.
- Right: output power of flip–flop as a function of time.
- Switching limited by carrier lifetime ($\sim$1 ns).
- Physical mechanism: Shift of stop band as refractive index changes in response to changes in carrier density.

Back
Close

DFB-Amplifier Flip-Flops

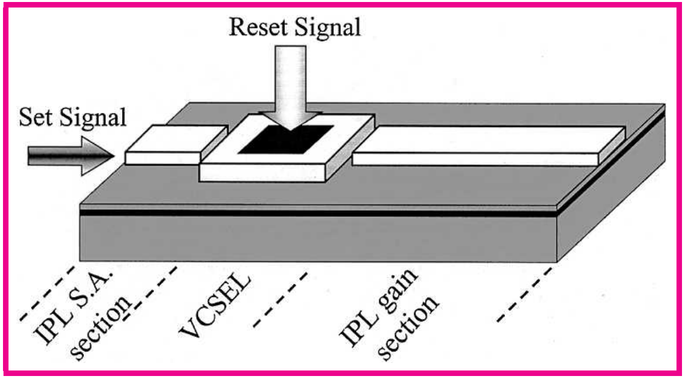
- Set pulse saturates SOA gain, reduces carrier density, and increases mode index $\bar{n}$.
- Bragg wavelength shifts to longer wavelengths ($\lambda_B = 2\bar{n}\Lambda$).
- Reset pulse is absorbed by SOA; resulting increase in the carrier density decreases $\bar{n}$.
- Bragg wavelength shifts toward shorter wavelengths.
- Set-pulse wavelength must be within the SOA gain bandwidth.
- Exact wavelength of reset pulse is not important as long as it falls outside the gain bandwidth and is absorbed.
- Polarization of reset pulse does not play any role.
- Control signals can propagate in either direction.

Synchronized Semiconductor Lasers



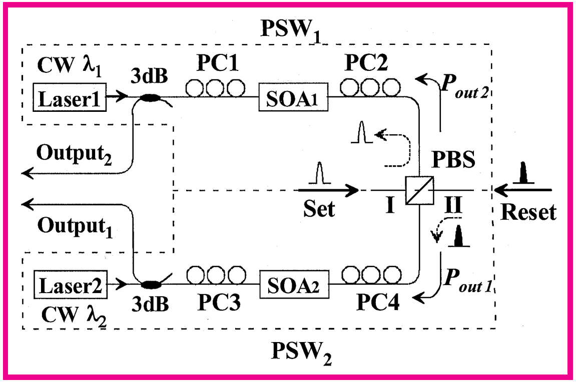
- Two lasers, each built using an SOA and two fiber Bragg gratings acting as mirrors, operate at wavelengths λ_1 and λ_2.
- One of the lasers is selectively turned off by injecting light at a wavelength different than its own (gain quenching).
- Output wavelength can be switched between λ_1 and λ_2 using optical controls.
- An optical flop-flop in which two coupled lasers are integrated on the same chip has been fabricated.

VCSEL-Based Flip–Flop



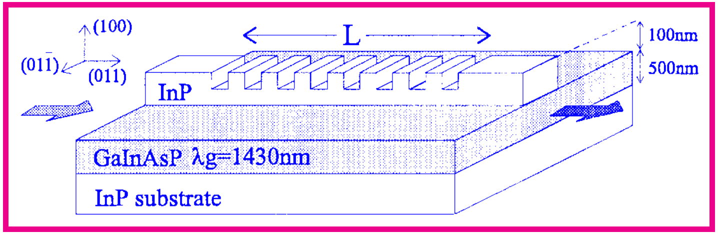
- A VCSEL is integrated with an in-plane laser (IPL) containing a short unbiased section acting as saturable absorber.
- Two lasers share the same active region and are mutually coupled.
- Edge-emitting laser biased such that its output is low (off state).
- Set pulse saturates absorber and turns laser on (on state).
- Device is turned off by injecting a reset pulse through VCSEL.

Polarization Switching



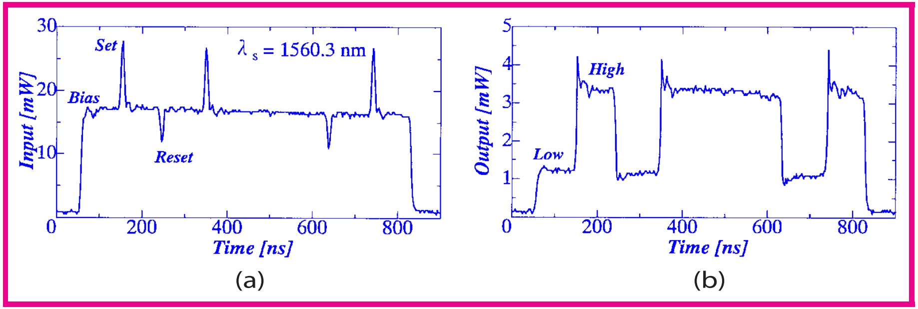
- SOAs made with strained quantum wells to enhance TE–TM gain difference.
- Gain difference changes with control power injected into each SOA.
- Two CW lasers act as holding beams.
- Set and reset pulses act as controls and are used to saturate the SOA gain.

Passive Semiconductor Waveguides



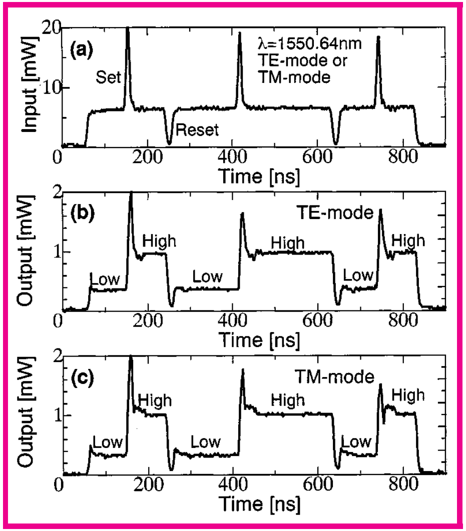
- Passive waveguides can be used for making flip-flops.
- Such devices operate below the bandgap and employ Kerr effect to change refractive index.
- Grating etched on the top InP cladding layer provides DFB needed for bistable operation.
- Device is biased at input power level such that it is close to but below the switching threshold.
- It is switched on and off by increasing or decreasing the input power.

Flip–Flop Performance



- Time-dependent input (a) and output (b) traces show performance of optical flip-flop.
- Required power levels are relatively large because of weaker nonlinearity compared with devices based on gain saturation.
- Kerr coefficient $n_2 = -4.5 \times 10^{-12}$ cm^2/W near 1,560 nm.
- For a 3-mm-long grating, set required 27 mW; reset occurred at 10-mW power levels

Polarization-Independent Flip-Flop



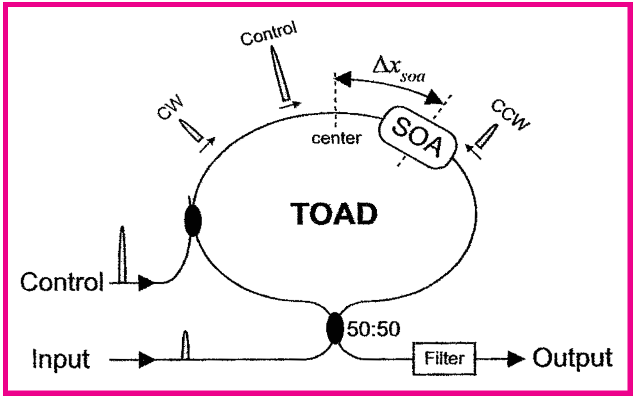
- Polarization-independent flip-flop realized using a passive waveguide integrated with a vertically etched Bragg reflector.
- Stop band of Bragg grating changed little when polarization of incident light was changed from the TE to TM mode.

• Virtually identical output for TE and TM polarizations.

Ultrafast Interferometric Switches

- Switches with a response time of 10 ps or so are needed for switching individual bits.
- Many devices make use of the nonlinear phenomenon of XPM.
- They convert phase modulation into amplitude modulation using a Sagnac interferometer (nonlinear optical loop mirror)
- A Mach–Zehnder interferometer made using directional couplers can also be used.
- Fiber-based devices often suffer from dispersive and environmental stability problems.
- These problems can be solved using a semiconductor optical amplifier as a nonlinear medium.

Sagnac-Loop with an SOA

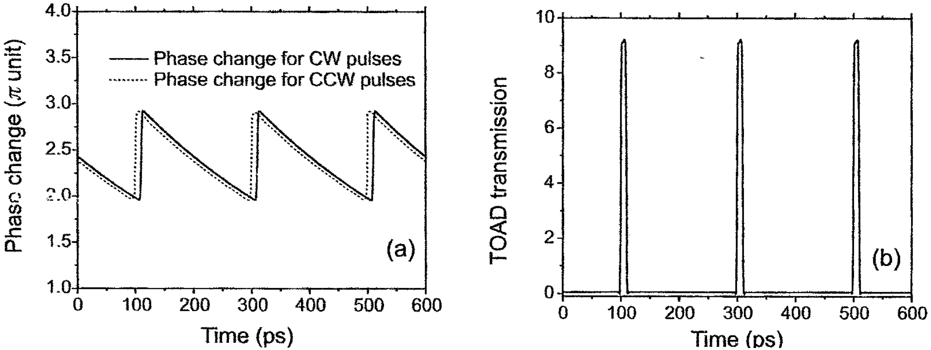


- Speed limitation of SOA is overcome by a clever trick.
- The SOA's location is shifted from the center of the loop by a small but precise distance.
- This shift governs temporal window over which switching occurs rather than the carrier lifetime.
- Such a device is referred to as SLALOM or TOAD.

Physics Behind TOAD

- Control pulse propagates in the CW direction and is intense enough to saturate the SOA.
- Control pulse is timed such that it arrives at SOA after CCW pulse but before the CW pulse.
- If this differential phase shift equals π, signal pulse is transmitted, rather than being reflected.
- Switching time is governed by the speed with which control pulse can saturate the SOA and change its refractive index.
- Switching process can be repeated as long as control pulses are separated by gain-recovery time.
- Control pulses must be injected at a relatively low rate (10 GHz or less).

Simple Model for TOAD



- Phase shift imposed by the control pulse equals $\phi(t) = -\frac{1}{2}\beta_c h(t)$, where $h(\tau) = \int_0^L g(z,\tau)\,dz$ (Section 5.5.4).
- Relative phase shift produced by the amplifier is given by $\Delta\phi(t) = \frac{1}{2}\beta_c[h(t) - h(t+t_d)]$, where $t_d = 2\Delta x_{\text{soa}}/v_g$.
- Transmissivity: $T(t) = \frac{1}{4}[G_1(t) + G_2(t) - 2\sqrt{G_1(t)G_2(t)}\cos[\Delta\phi(t)]$.
- G_1 and G_2 represent SOA gains for the CW and CCW directions, respectively.

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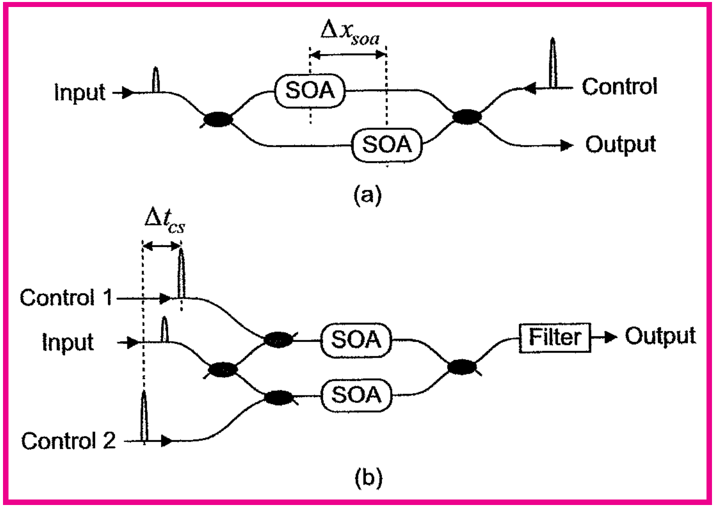
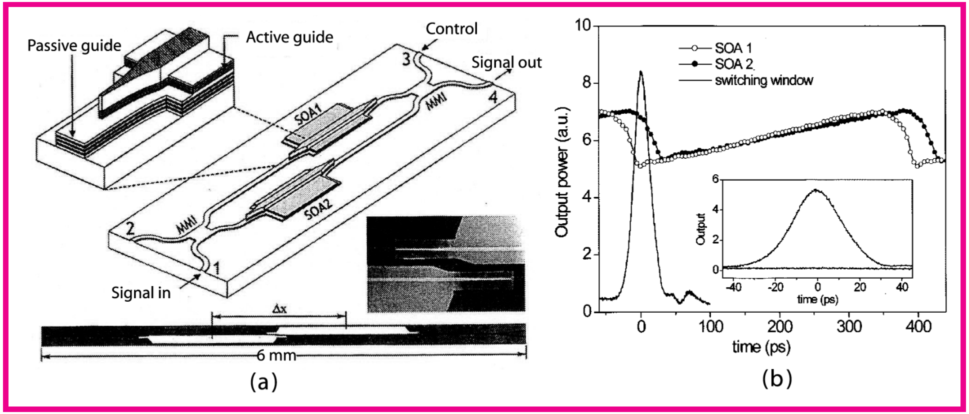
Mach–Zehnder Switches



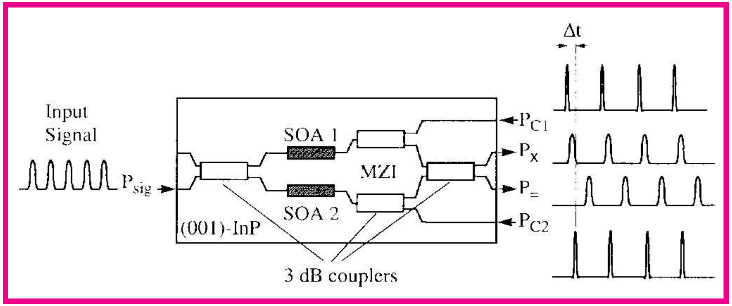
- (a) colliding-pulse MZ switch; (b) symmetric MZ switch
- Use of SOA as the nonlinear medium reduces arm lengths.
- Such device can be integrated on a single chip.
- In the case of symmetric MZ switch, asymmetry is introduced by the relative delay between two control pulses.

Asymmetric Mach–Zehnder Switch



- Switch fabricated in a monolithic form using InP waveguides.
- MZ interferometer built using two 3-dB MMI couplers.
- Two 1.5-mm-long SOAs are offset by 1.5 mm; this distance sets the switching window to about 20 ps.
- Measured gain variations in the two SOAs and the resulting switching window.

Symmetric Mach–Zehnder Switch

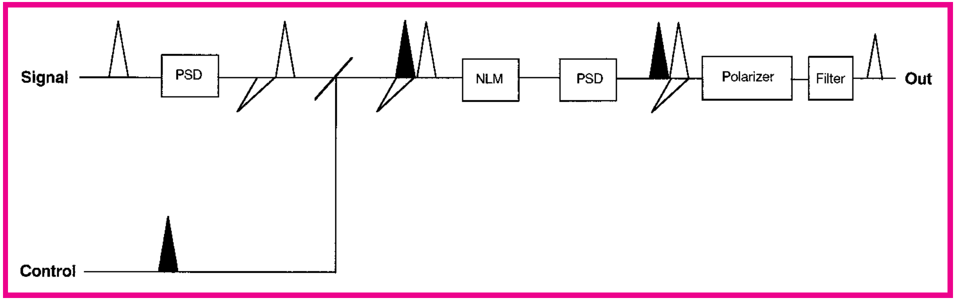


- Layout of a monolithically integrated symmetric MZ switch fabricated on an InP substrate.
- Signal and control pulses show how such a device can be used as an OTDM demultiplexer.
- Two control pulses are delayed by a time interval Δt that sets duration of the switching window.
- Main advantage: Delay time can be adjusted externally.

Polarization-Discriminating Switches

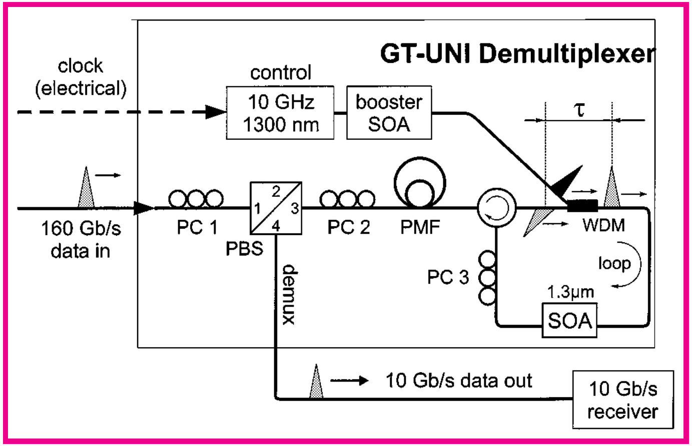
- Stability of a MZ interferometer is ensured by adopting a single-arm MZ design.
- Same physical path shared by two orthogonally polarized components of signal pulse.
- Relative delay between orthogonally polarized pulses is produced by a polarization-maintaining fiber.
- Such a switch is referred to as an ultrafast nonlinear interferometric (UNI) switch.
- The nonlinear element can be a passive waveguide but SOAs are also used in practice.

Ultrafast Nonlinear Interferometer



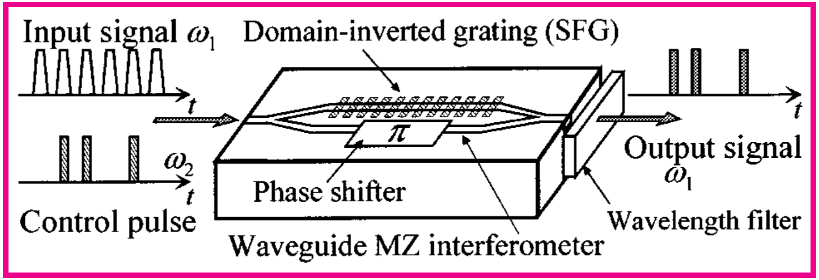
- Orthogonally polarized components of signal pulse delayed using a PMF by $\Delta t = |n_x - n_y|L/c$.
- Timing of control pulse adjusted such that it overlaps with one component but not the other.
- Two components synchronized by a second PMF whose fast and slow axes are reversed.
- A polarizer set at 45° forces interference between the two polarization components.

UNI with SOA in a Loop



- The same PMF used to split and recombine signal pulses.
- XPM-induced phase shift produced inside an SOA.
- Relative phase shift between two polarization components is used to switch signal pulse to the output port 4.
- SOA operates in the gain-transparent regime (signal wavelength below the bandgap).

Lithium-Niobate Switches



- Sum-frequency generation in a PPLN is used for switching.
- PPLN placed in one arm of the MZ interferometer.
- A thin-film heater incorporated into the other arm.
- The whole device can be integrated on a single chip (1 cm long).
- Quasi-phase matching period was 18 μm over a 5-mm-long section.
- Dispersive effects limit switching time to a few picoseconds.

Optical Time-Domain Demultiplexing

- An OTDM signal consists of a high-speed bit stream composed of several channels.
- If 10 channels at 10 Gb/s are multiplexed, every 10th bit of the 100-Gb/s bit stream belongs to the same channel.
- Demultiplexing requires optical switches that direct all bits belonging to a specific channel to a different port.
- Such switches require control pulses at channel bit rate.
- This control pulse train is referred to as an optical clock.
- Switch must respond on a time scale of a few picosecond to select individual bits from the composite bit stream.

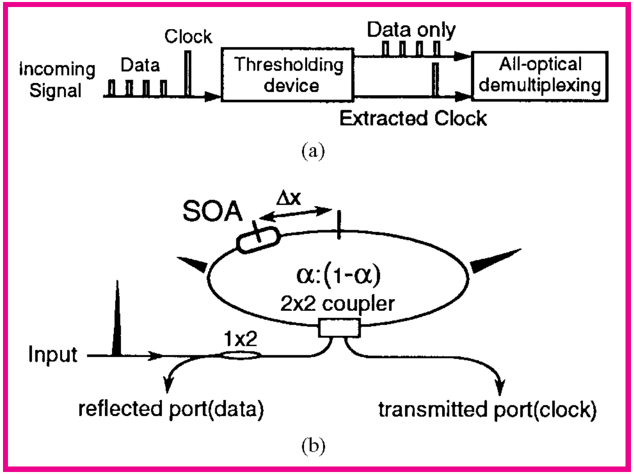
Optical-Clock Recovery

- Demultiplexing of an OTDM signal requires an optical clock.
- This clock should be generated from the OTDM signal itself.
- In self-clocked networks, clock pulses are sent with the signal.
- One needs to separate clock pulses from the data and direct them to a different port.
- If clock pulses are at a different wavelength, an optical filter can be used to recover the clock.
- This method suffers from clock skew induced by group-velocity mismatch.
- Better approach: Clock pulses have the same wavelength but are made much more intense than data pulses.

Optical-Clock Recovery

(a) Self-clocking scheme for OTDM networks

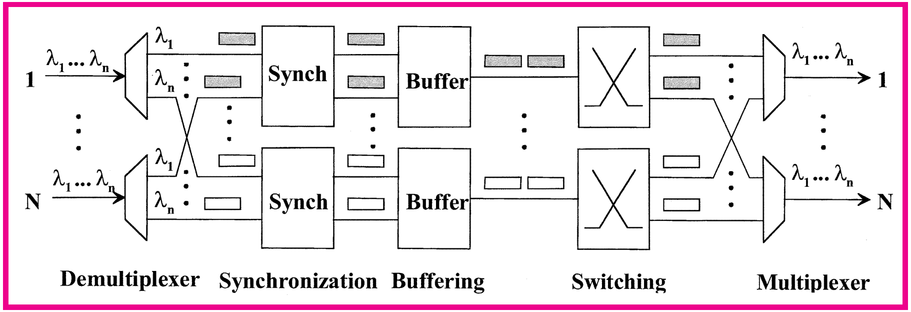
(b) Sagnac-loop switch used to separate the clock.



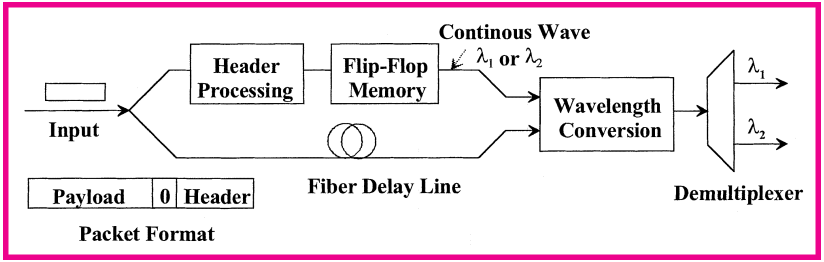
- Coupler designed with $\alpha \approx 0.2$ so that clockwise pulse closer to the SOA is much less intense.
- The CCW clock pulse enters the SOA later, and SPM-induced phase shift sends clock pulses to a different port.
- Data pulses arrive at the SOA after switching window has closed.

Packet-Switched Networks

- Packet-switched networks route data using packets consisting of hundreds of bits.
- Each packet begins with a header that contains destination information.
- A router reads the header and sends it toward its destination.
- At bit rates of 10 Gb/s or more, packets must be switched optically.
- Design of an all-optical packet-switched cross-connect.

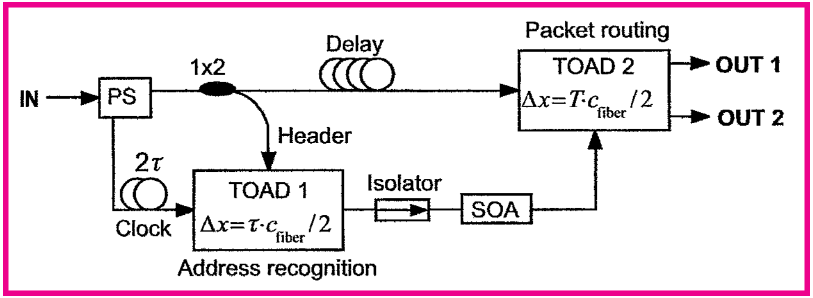


Packet-Switching Unit



- Design of an 1×2 packet switch; output is produced at two different wavelengths depending on header address.
- One branch processes header, while other delivers the payload.
- Header-processing unit employs a Sagnac loop for switching.
- Flip-flop memory is implemented using two coupled lasers that switch output between two wavelengths.
- A wavelength converter used to produce output at different wavelengths depending on the header information.

Packet-Switching with Sagnac Loops

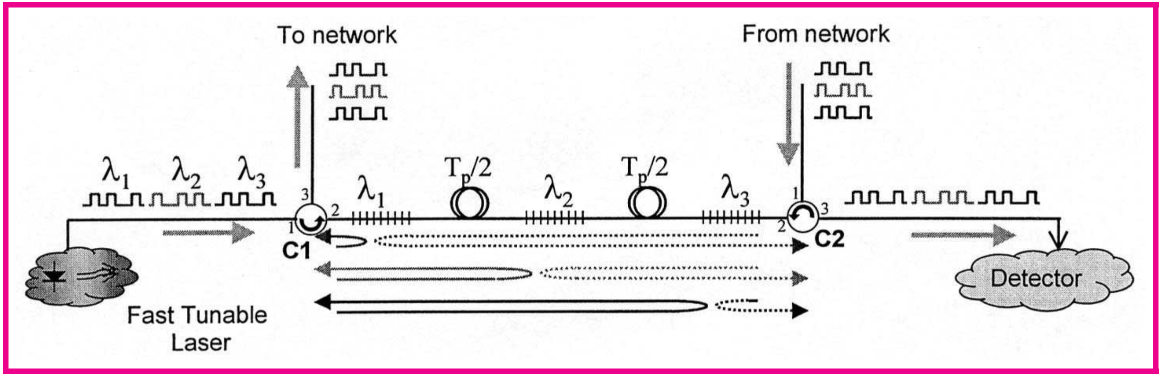


- Design of an 1×2 packet switch based on two TOAD devices.
- It switches packets to different output ports depending on a single header bit.
- Clock bits are sent with data using orthogonal polarization and are separated with the help of a polarization splitter.
- This clock is used in the first TOAD (with a narrow switching window) to demultiplex a single header bit.

Packet-Switching with Sagnac Loops

- The header bit acts as control pulse for the second TOAD whose switching window remains open for the duration of the entire packet.
- When header bit corresponds to 1, the packet is transmitted (output port 1).
- If header bit is 0, packet is reflected and appears at output port 2 after passing through a circulator.
- Time delay τ in the first TOAD corresponds to the duration of a single bit within the packet.
- For the second TOAD, time delay $T = N\tau$, where N is the number of bits within the packet.

Multiwavelength Packets



- Packets at different wavelengths transmitted simultaneously.
- Serial Packets at different wavelengths are combined to produce a multiwavelength packet using fiber gratings and delay lines.
- The same device can be used to demultiplex composite packets.
- Packets can be added or dropped at intermediate nodes using 2×2 switches.